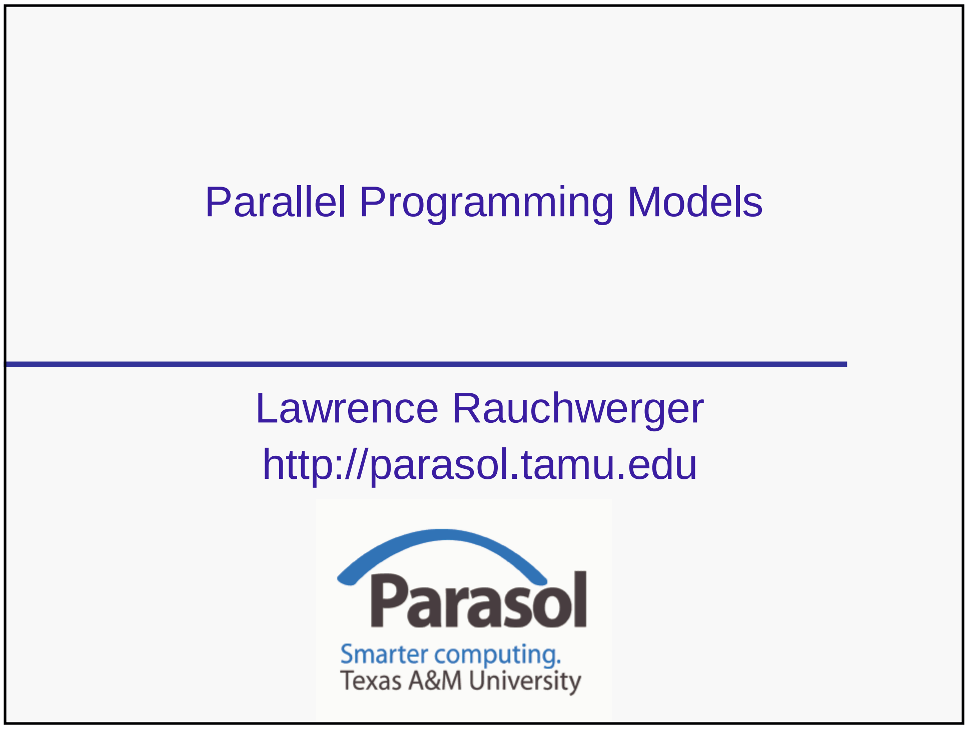
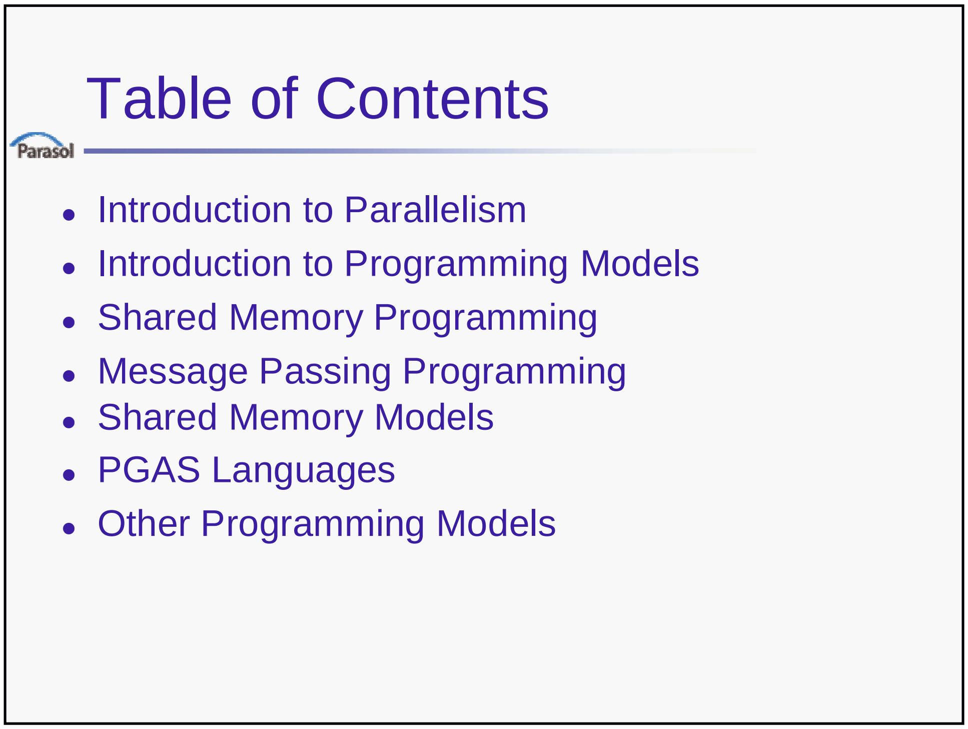


Parallel Programming Models

Lawrence Rauchwerger
http://parasol.tamu.edu

Parasol
Smarter computing.
Texas A&M University



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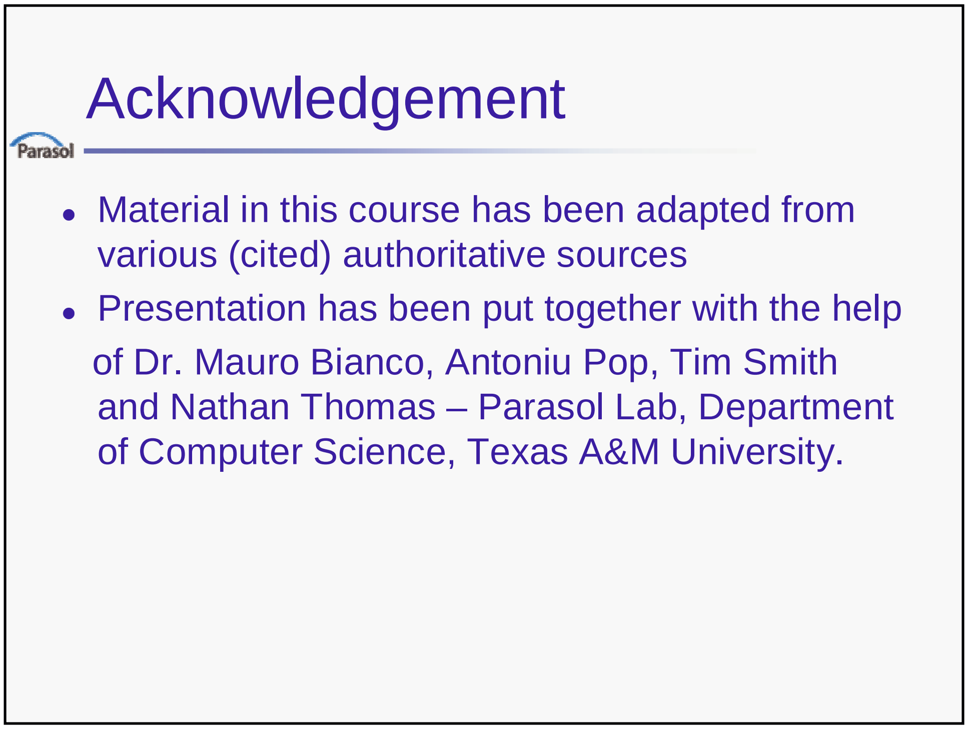
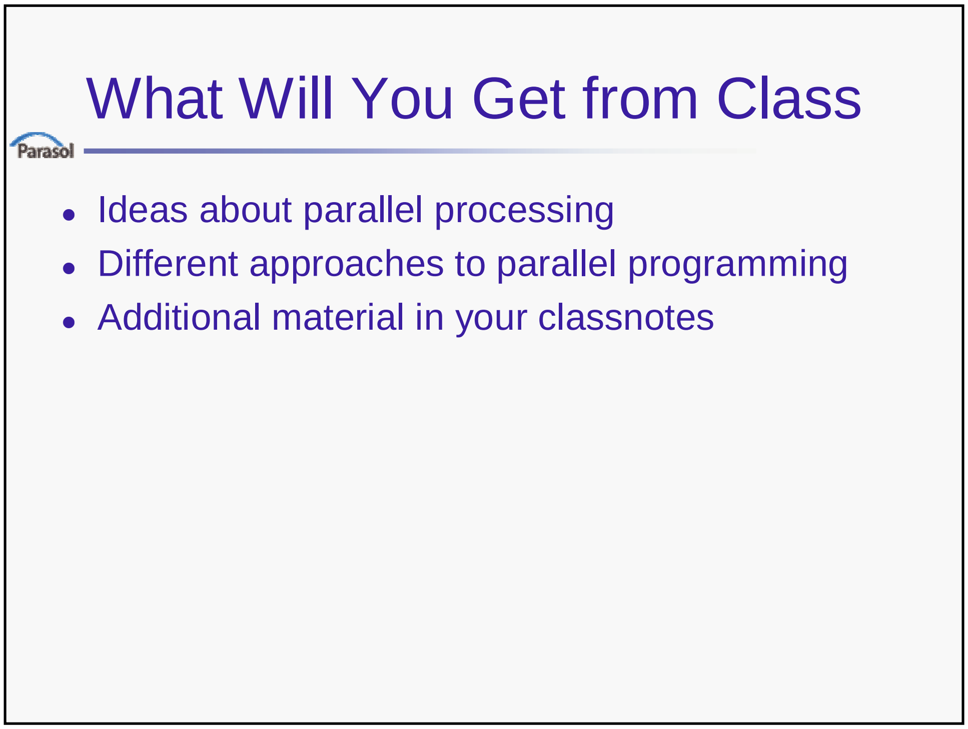


Acknowledgement

- Material in this course has been adapted from various (cited) authoritative sources
- Presentation has been put together with the help of Dr. Mauro Bianco, Antoniu Pop, Tim Smith and Nathan Thomas – Parasol Lab, Department of Computer Science, Texas A&M University.



What Will You Get from Class

- Ideas about parallel processing
- Different approaches to parallel programming
- Additional material in your classnotes

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- Introduction to Parallelism
  - What is Parallelism ? What is the Goal ?
- Introduction to Programming Models
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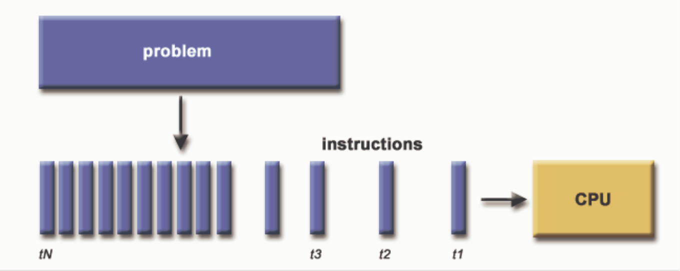
Introduction to Parallelism

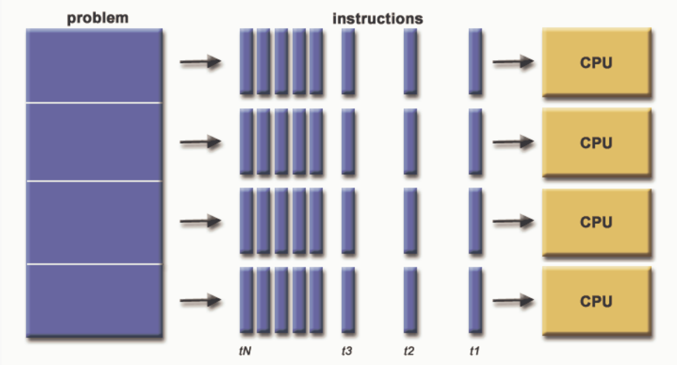
- Sequential Computing
  - Single CPU executes stream of instructions.



Adapted from: http://www.llnl.gov/computing/tutorials/parallel_comp

Introduction to Parallelism

- Parallel computing
  - Partition problem into multiple, concurrent streams of instructions.



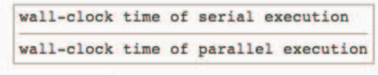
Classification

Flynn's Taxonomy (1966-now)		Nowadays
SISD *Single Instruction* *Single Data*	**SIMD** *Single Instruction* *Multiple Data*	**SPMD** *Single Program* *Multiple Data*
MISD *Multiple Instructions* *Single Data*	**MIMD** *Multiple Instructions* *Multiple Data*	**MPMD** *Multiple Program* *Multiple Data*

- Execution models impact the above programming model
- Traditional computer is SISD
- SIMD is *data parallelism* while MISD is pure *task parallelism*
- MIMD is a mixed model (harder to program)
- SPMD and MPMD are less synchronized than SIMD and MIMD
- SPMD is most used model, but MPMD is becoming popular

Introduction to Parallelism

- Goal of parallel computing
  - Save time - reduce wall clock time.
    - Speedup ·



$$\frac{\texttt{wall-clock time of serial execution}}{\texttt{wall-clock time of parallel execution}}$$

  - Solve larger problems - problems that take more memory than available to 1 CPU.

Reduce wall clock time

- Methods
  - Parallelizing serial algorithms (parallel loops)
    - Total number of operations performed changes only slightly
    - Scalability may be poor (Amdahl's law)
  - Develop parallel algorithms
    - Total number of operations may increase, but the running time decreases
- Work Complexity
  - Serialization: parallel algorithm executed sequentially Serializing parallel algorithm may lead to sub-optimal sequential complexity

Performance Models

- Abstract Machine Models (PRAM, BSP, and many, many others)
  - Allow asymptotical analysis and runtime estimations
  - Often inaccurate for selecting the right implementation/algorithm on a given architecture
- Programming Primitives Behavior
  - Allow the selection of the right implementation
  - Increases programming effort

Abstract Machine

- PRAM (Parallel RAM, shared memory)
  - Processors access a shared flat memory
  - Performing an operation or accessing a memory location has cost = 1
- BSP (Bulk Synchronous Parallel, distributed memory)
  - Computation proceeds through supersteps
  - Cost of a superstep is *w+hg+l*
  - *w* is the time for computing on local data
  - *h* is the size of the largest message sent
  - *g* and *l* are architectural parameters describing network bandwidth and latency, respectively

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  - Performance
  - Portability
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- Message Passing Programming
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- PGAS Languages
- Other Programming Models

Parallel Programming Models

Many languages and libraries exist for creating parallel applications.

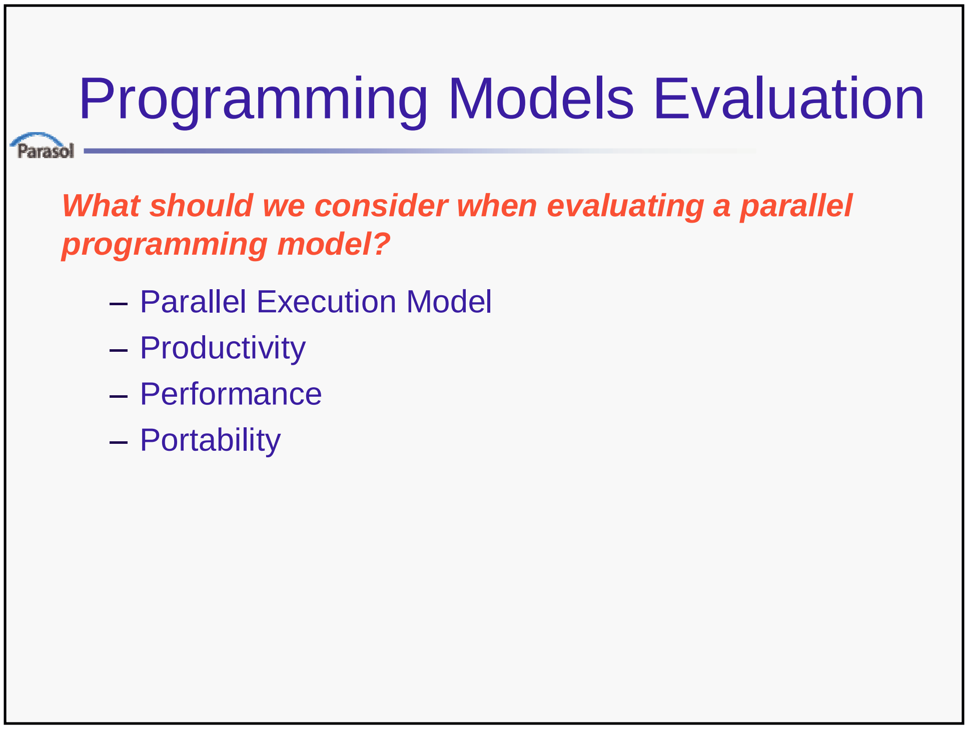
Each presents a programming model to its users.

During this course, we'll discuss criteria for evaluating a parallel model and use them to explore various approaches.

OpenMP
Pthreads
Cilk
TBB
HPF
MPI

Charm++
UPC
STAPL
X10
Fortress
Chapel

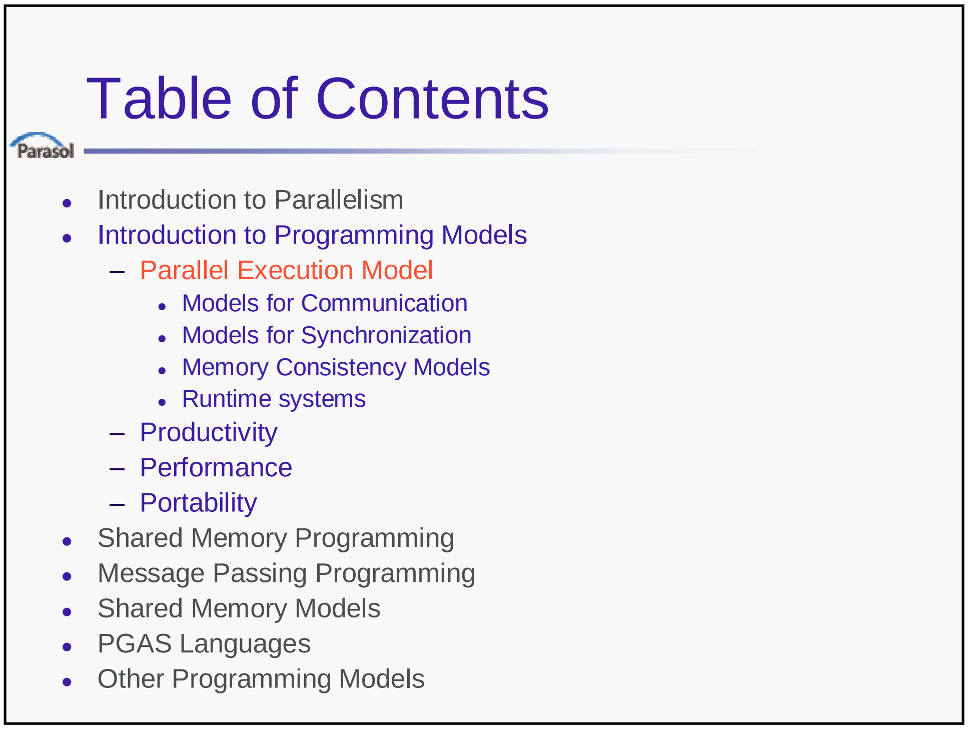
Linda
MapReduce
Matlab DCE



Programming Models Evaluation

What should we consider when evaluating a parallel programming model?

- – Parallel Execution Model
- – Productivity
- – Performance
- – Portability



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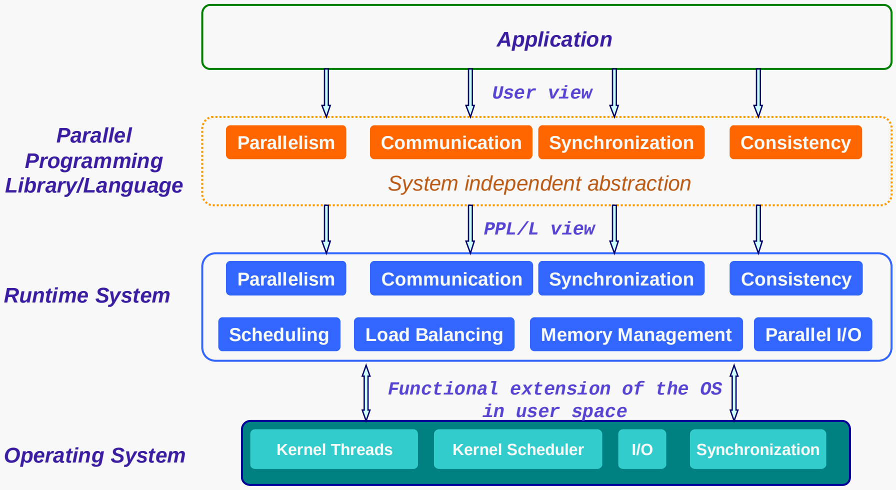
Exec Model Productivity Performance Portability

Parallel Execution Model

Parasol



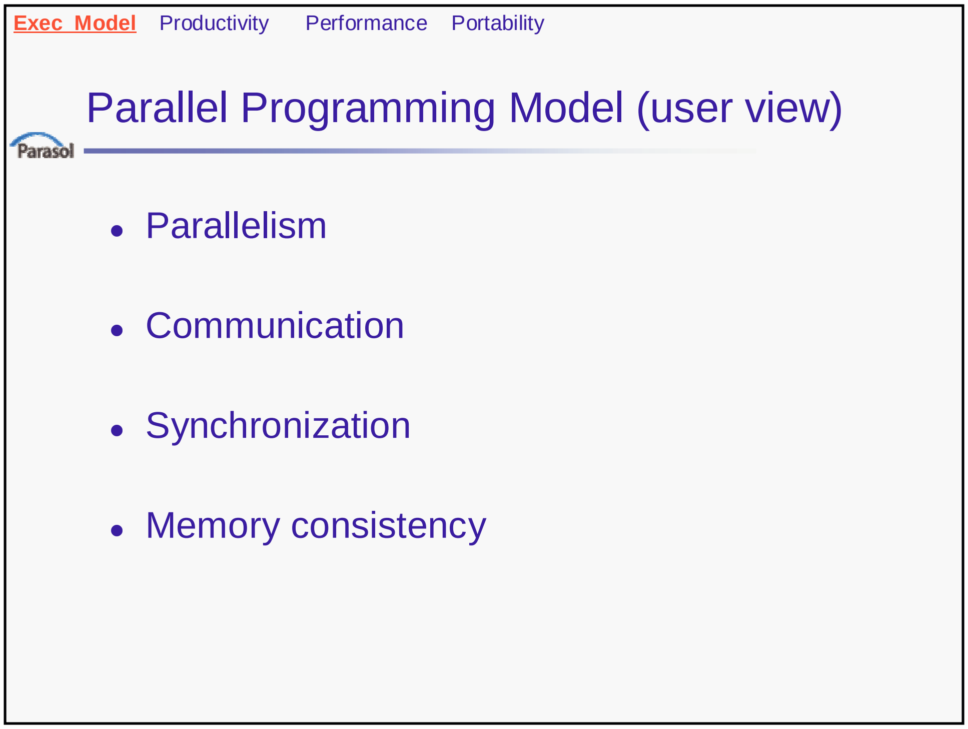
Exec Model Productivity Performance Portability

Parallel Execution Model

Parasol

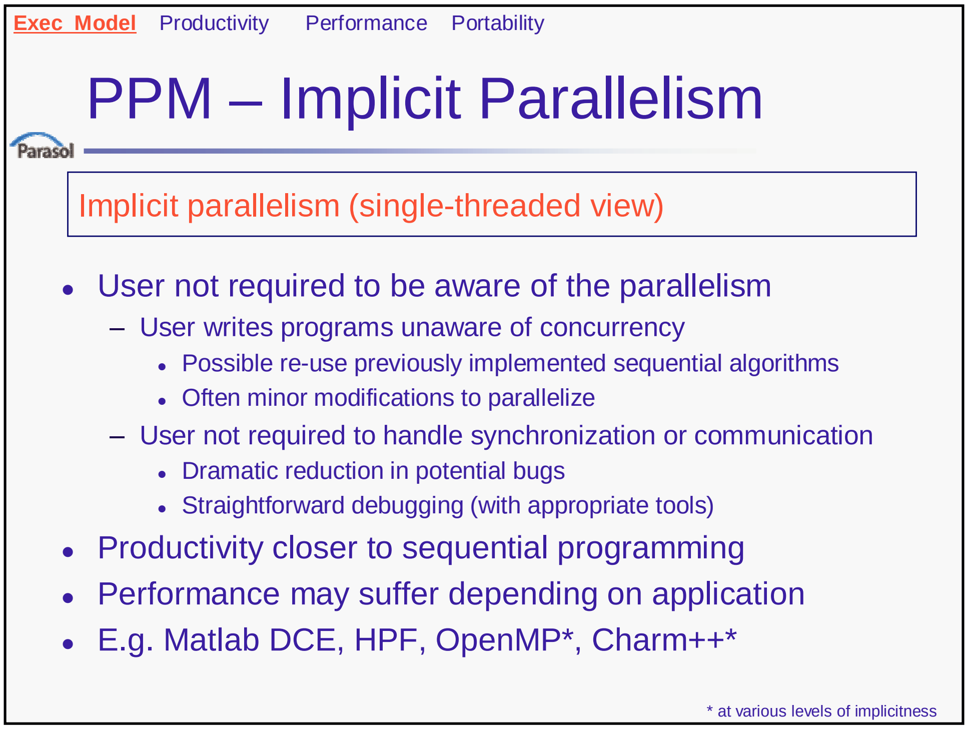
- Parallel Programming Model (user view)
  - Parallelism
  - Communication
  - Synchronization
  - Memory consistency

- Runtime System (RTS)
  - Introduction, definition and objectives
  - Usual services provided by the RTS
  - Portability / Abstraction



Parallel Programming Model (user view)

- Parallelism
- Communication
- Synchronization
- Memory consistency

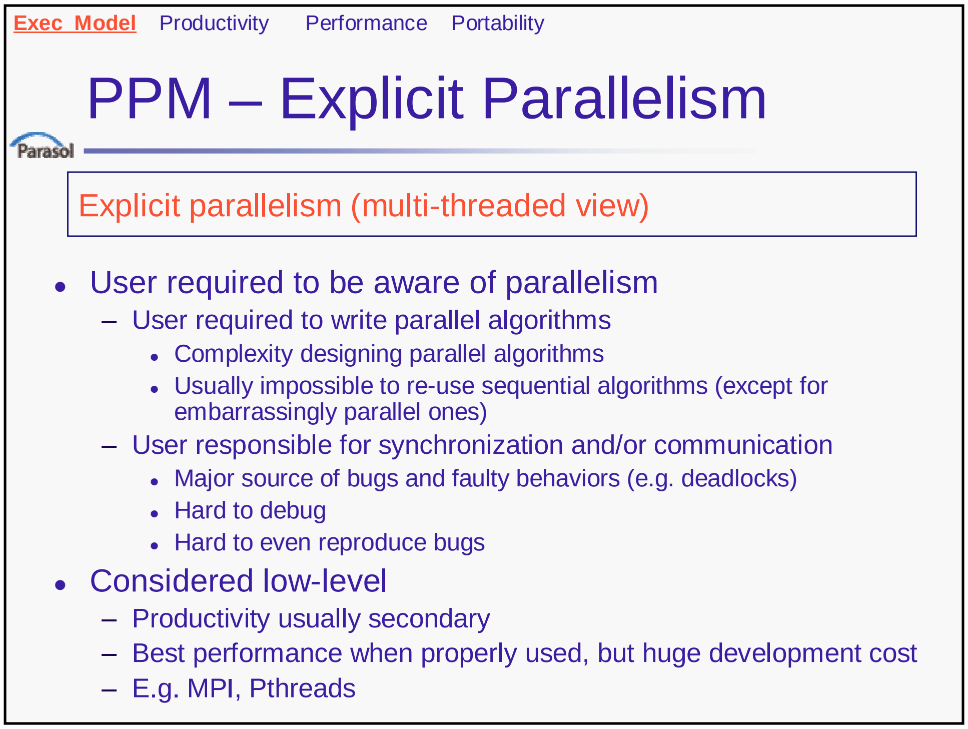


PPM – Implicit Parallelism

Implicit parallelism (single-threaded view)

- User not required to be aware of the parallelism
  - User writes programs unaware of concurrency
    - Possible re-use previously implemented sequential algorithms
    - Often minor modifications to parallelize
  - User not required to handle synchronization or communication
    - Dramatic reduction in potential bugs
    - Straightforward debugging (with appropriate tools)
- Productivity closer to sequential programming
- Performance may suffer depending on application
- E.g. Matlab DCE, HPF, OpenMP*, Charm++*

* at various levels of implicitness

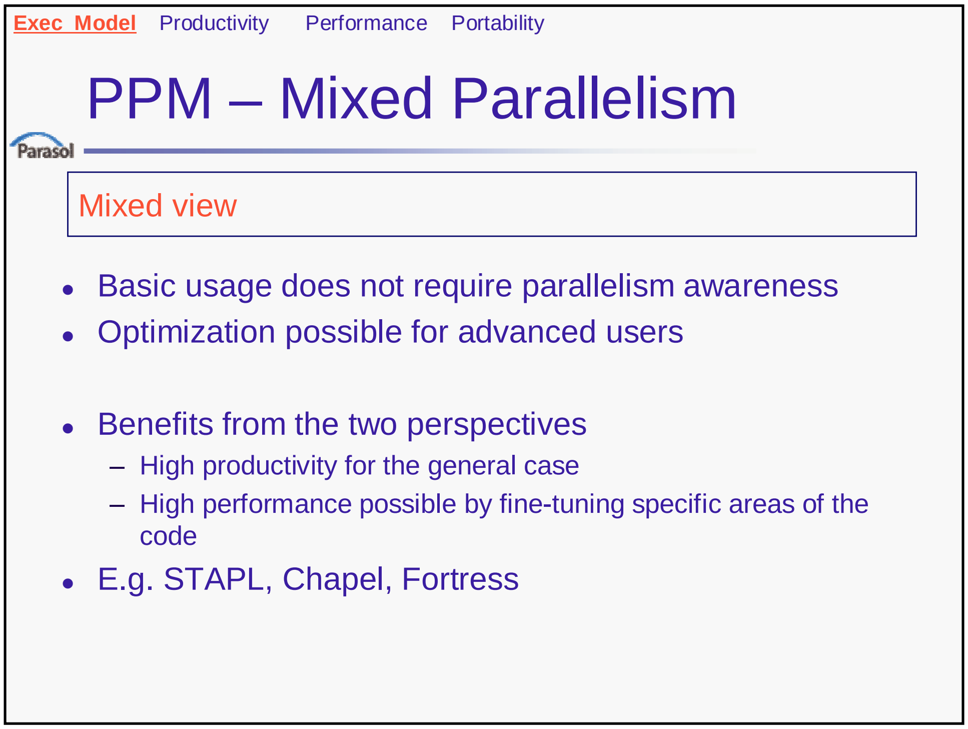


Exec Model Productivity Performance Portability

PPM – Explicit Parallelism

Explicit parallelism (multi-threaded view)

- User required to be aware of parallelism
  - User required to write parallel algorithms
    - Complexity designing parallel algorithms
    - Usually impossible to re-use sequential algorithms (except for embarrassingly parallel ones)
  - User responsible for synchronization and/or communication
    - Major source of bugs and faulty behaviors (e.g. deadlocks)
    - Hard to debug
    - Hard to even reproduce bugs
- Considered low-level
  - Productivity usually secondary
  - Best performance when properly used, but huge development cost
  - E.g. MPI, Pthreads



Exec Model Productivity Performance Portability

PPM – Mixed Parallelism

Mixed view

- Basic usage does not require parallelism awareness
- Optimization possible for advanced users

- Benefits from the two perspectives
  - High productivity for the general case
  - High performance possible by fine-tuning specific areas of the code
- E.g. STAPL, Chapel, Fortress

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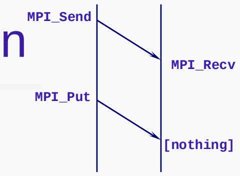
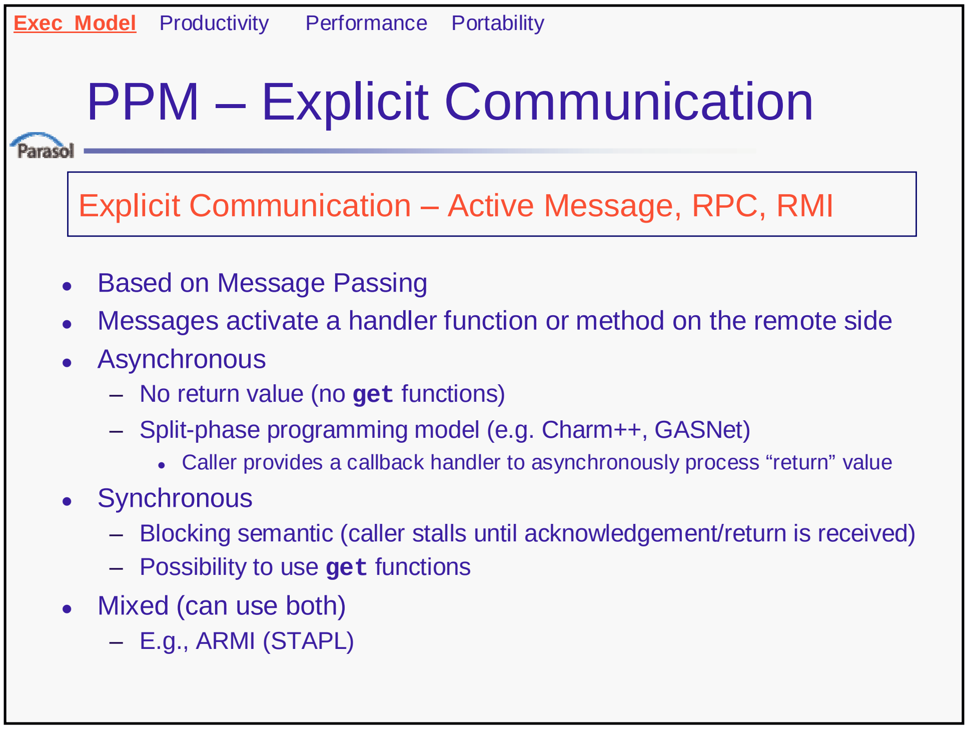
Exec Model Productivity Performance Portability

PPM – Explicit Communication



Explicit Communication

- Message Passing (two-sided communication, P2P)
  - User explicitly sends/receives messages (e.g., MPI)
  - User required to match every Send operation with a Receive
  - Implicitly synchronizes the two threads
    - Often excessive synchronization (reduces concurrency)
    - Non-blocking operations to alleviate the problem (e.g., MPI_Isend/Recv)
- One-sided communication
  - User uses get/put operations to access memory (e.g., MPI-2, GASNet, Cray T3D)
  - No implicit synchronization (i.e., asynchronous communication)

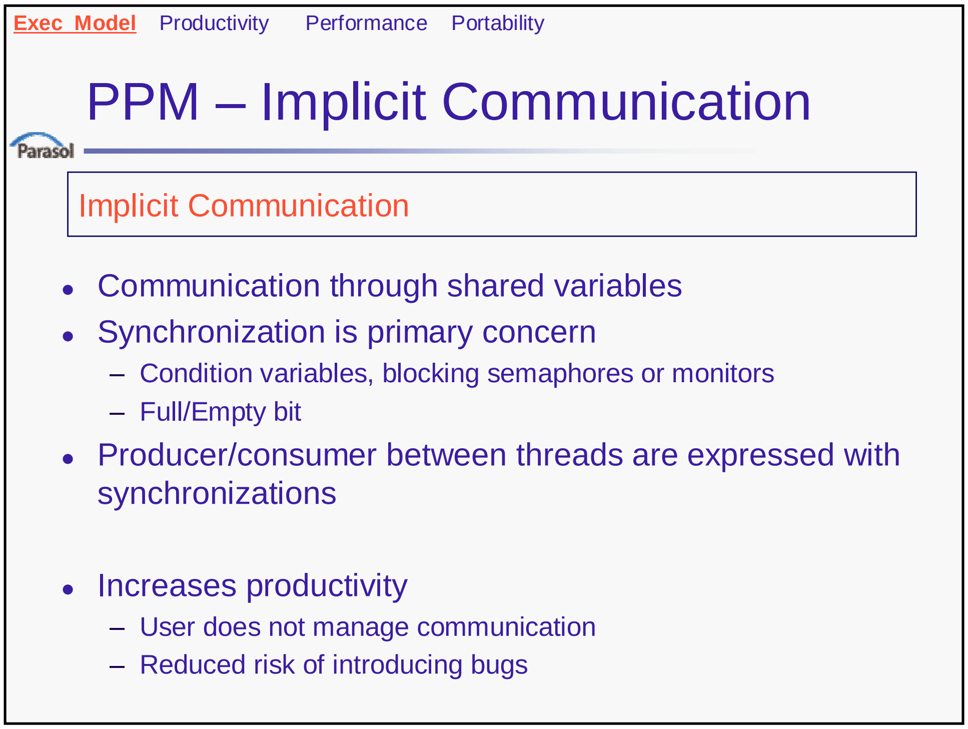


Exec Model Productivity Performance Portability

PPM – Explicit Communication

Explicit Communication – Active Message, RPC, RMI

- Based on Message Passing
- Messages activate a handler function or method on the remote side
- Asynchronous
  - No return value (no **`get`** functions)
  - Split-phase programming model (e.g. Charm++, GASNet)
    - Caller provides a callback handler to asynchronously process “return” value
- Synchronous
  - Blocking semantic (caller stalls until acknowledgement/return is received)
  - Possibility to use **`get`** functions
- Mixed (can use both)
  - E.g., ARMI (STAPL)



Exec Model Productivity Performance Portability

PPM – Implicit Communication

Implicit Communication

- Communication through shared variables
- Synchronization is primary concern
  - Condition variables, blocking semaphores or monitors
  - Full/Empty bit
- Producer/consumer between threads are expressed with synchronizations

- Increases productivity
  - User does not manage communication
  - Reduced risk of introducing bugs

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Exec Model Productivity Performance Portability

PPM – Explicit Synchronization

Parasol

Explicit Synchronization

- Critical section / locks
  - One thread allowed to execute the guarded code at a time
- Condition variables / blocking semaphores
  - Producer/consumer synchronization
  - Introduces order in the execution
- Monitors / counting semaphores
  - Shared resources management
- Barrier / Fence (global synchronization)
  - Threads of execution wait until all reach the same point
- E.g., Pthreads, TBB, OpenMP

Exec Model Productivity Performance Portability

PPM – Implicit Synchronization

Implicit Synchronization

- Hidden in communication operations (e.g., two-sided communication)
- Data Dependence Graph (DDG)
  - PPL synchronizes where necessary to enforce the dependences
  - E.g., STAPL
- Distributed Termination Detection
  - When implemented as background algorithm (e.g., in Charm++)
- Improved productivity
  - Less bugs from race conditions, deadlocks …
- E.g., STAPL, Charm++, MPI-1 and GASNet (to a certain extent)

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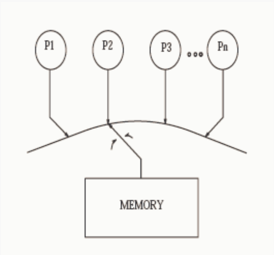
PPM – Memory Consistency

Introduction to Memory Consistency

- Specification of the effect of Read and Write operations on the memory
- Usual user assumption : Sequential Consistency

Definition: [A multiprocessor system is sequentially consistent if] the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.

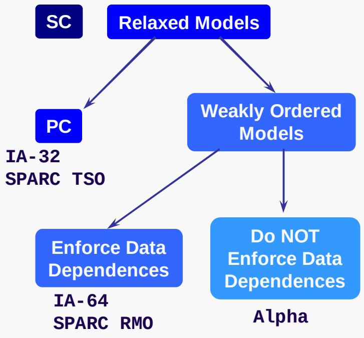


PPM – Memory Consistency

Introduction to Memory Consistency

Sequential Consistency: Don’t assume it !

- Sequential Consistency (SC)
  - MIPS/SGI
  - HP PA-RISC
- Processor Consistency (PC)
  - *Relax write→read dependencies*
  - Intel x86 (IA-32)
  - Sun TSO (Total Store Order)
- Relaxed Consistency (RC)
  - *Relax all dependencies, but add fences*
  - DEC Alpha
  - IBM PowerPC
  - Intel IPF (IA-64)
  - Sun RMO (Relaxed Memory Order)



SC

Relaxed Models

PC

IA-32
SPARC TSO

Weakly Ordered Models

Enforce Data Dependences

IA-64
SPARC RMO

Do NOT Enforce Data Dependences

Alpha

Material from: Hill, M. D. 2003. Revisiting "Multiprocessors Should Support Simple Memory Consistency Models" , http://www.cs.wisc.edu/multifacet/papers/dagstuhl03_memory_consistency.ppt

PPM – Memory Consistency

Introduction to Memory Consistency

Example :

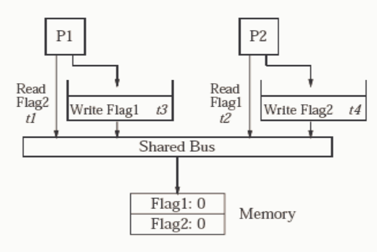
```
// Dekker's algorithm for critical sections
// Initially Flag1 = Flag2 = 0
```

```
              P1
Flag1 = 1;        W(Flag1)
If (Flag2 == 0) R(Flag2)
// critical section
...
```

```
              P2
Flag2 = 1;        W(Flag2)
if (Flag1 == 0) R(Flag1)
// critical section
...
```

Correct execution if a processor's Read operation returns 0 iff its Write operation occurred before both operations on the other processor.

- Relaxed consistency : buffer write operations
  - Breaks Sequential Consistency
  - Invalidates Dekker's algorithm
  - Write operations delayed in buffer



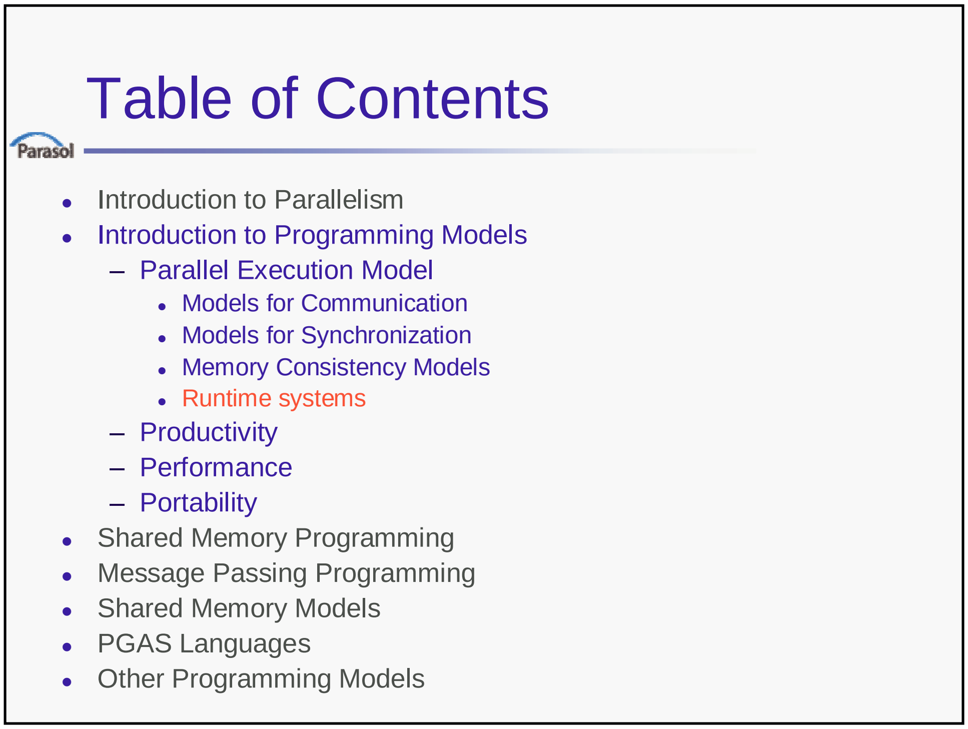
Material from & further reading: Adve, S. V. and Gharachorloo, K. 1996. Shared Memory Consistency Models: A Tutorial. Computer 29, 12 (Dec. 1996), 66-76. DOI= http://dx.doi.org/10.1109/2.546611

PPM – Memory Consistency

Relaxed Memory Consistency Models

- Improve performance
  - Reduce the ordering requirements
  - Reduce the observed memory latency (hides it)

- Common practice
  - Compilers freely reorder memory accesses when there are no dependences
  - Prefetching
  - Transparent to the user



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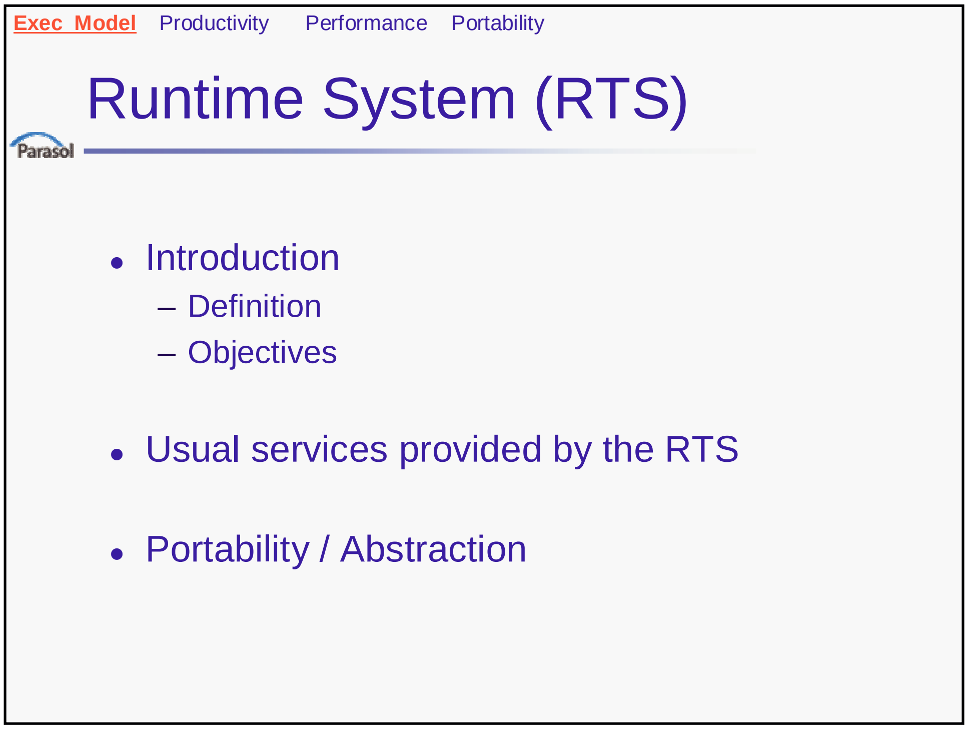
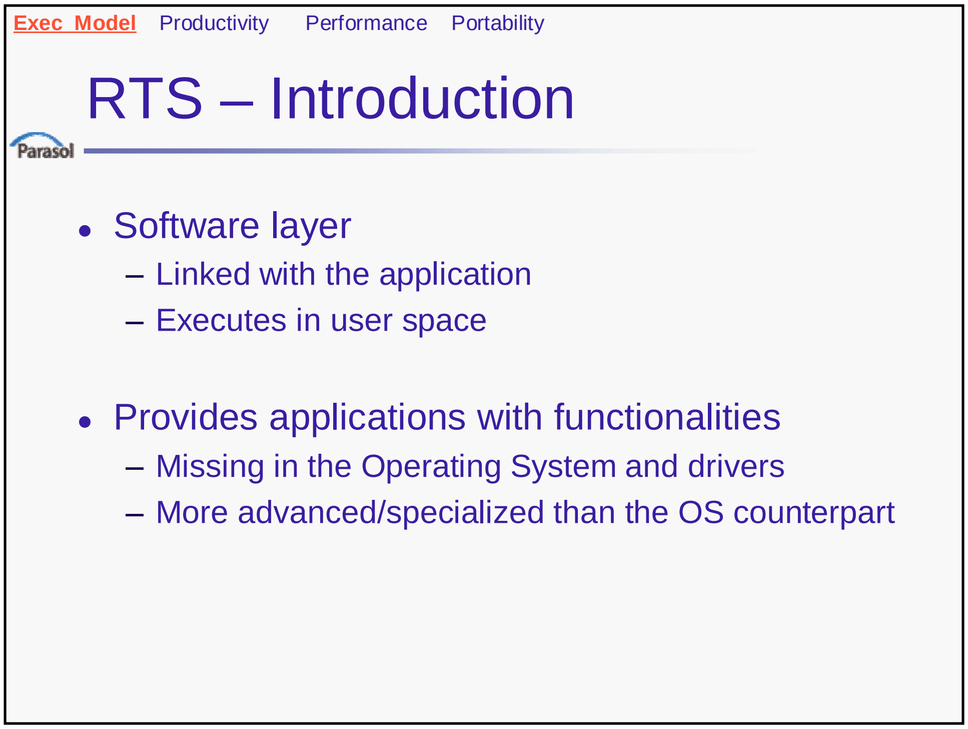


Exec Model Productivity Performance Portability

Runtime System (RTS)

Parasol

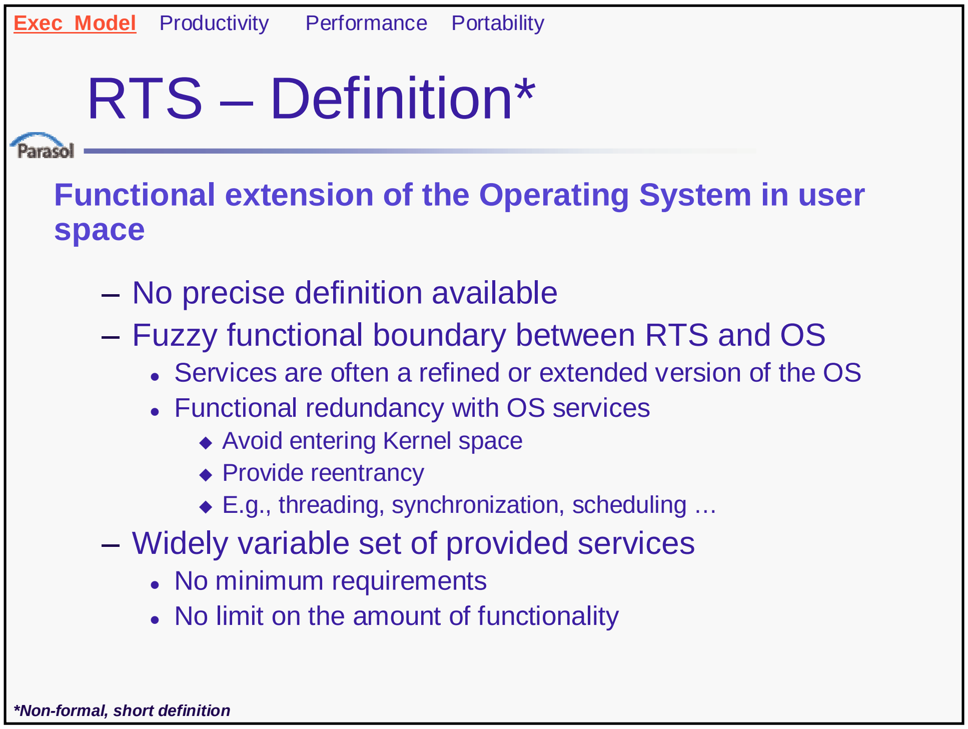
- Introduction
  - Definition
  - Objectives
- Usual services provided by the RTS
- Portability / Abstraction



RTS – Introduction

- Software layer
  - – Linked with the application
  - – Executes in user space

- Provides applications with functionalities
  - – Missing in the Operating System and drivers
  - – More advanced/specialized than the OS counterpart

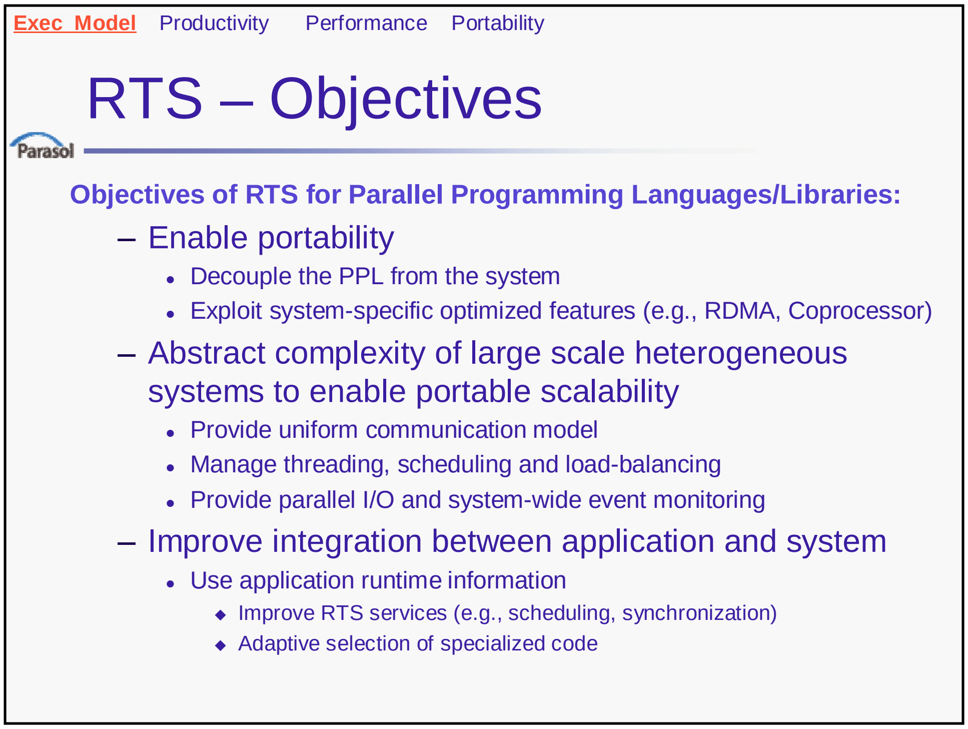


RTS – Definition*

Functional extension of the Operating System in user space

- – No precise definition available
- – Fuzzy functional boundary between RTS and OS
  - Services are often a refined or extended version of the OS
  - Functional redundancy with OS services
    - ◆ Avoid entering Kernel space
    - ◆ Provide reentrancy
    - ◆ E.g., threading, synchronization, scheduling …
- – Widely variable set of provided services
  - No minimum requirements
  - No limit on the amount of functionality

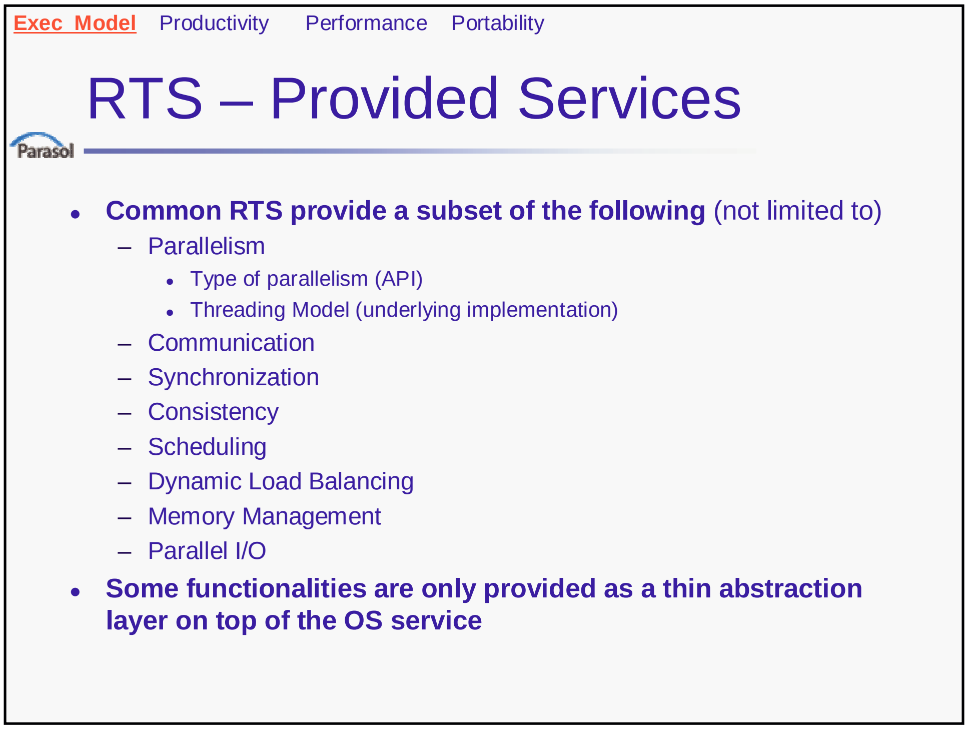
Non-formal, short definition



RTS – Objectives

Objectives of RTS for Parallel Programming Languages/Libraries:

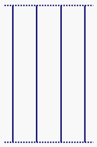
- Enable portability
  - Decouple the PPL from the system
  - Exploit system-specific optimized features (e.g., RDMA, Coprocessor)
- Abstract complexity of large scale heterogeneous systems to enable portable scalability
  - Provide uniform communication model
  - Manage threading, scheduling and load-balancing
  - Provide parallel I/O and system-wide event monitoring
- Improve integration between application and system
  - Use application runtime information
    - Improve RTS services (e.g., scheduling, synchronization)
    - Adaptive selection of specialized code



RTS – Provided Services

- **Common RTS provide a subset of the following** (not limited to)
  - Parallelism
    - Type of parallelism (API)
    - Threading Model (underlying implementation)
  - Communication
  - Synchronization
  - Consistency
  - Scheduling
  - Dynamic Load Balancing
  - Memory Management
  - Parallel I/O
- **Some functionalities are only provided as a thin abstraction layer on top of the OS service**

RTS – Flat Parallelism

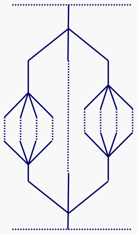


Parallelism types – Flat Parallelism

- All threads of execution have the same status
  - No parent/child relationship
- Threads are active during the whole execution
- Usually constant number of threads of execution

- Well adapted for problems with large granularity
- Difficult to achieve load-balance for non-embarrassingly parallel applications
- E.g. MPI

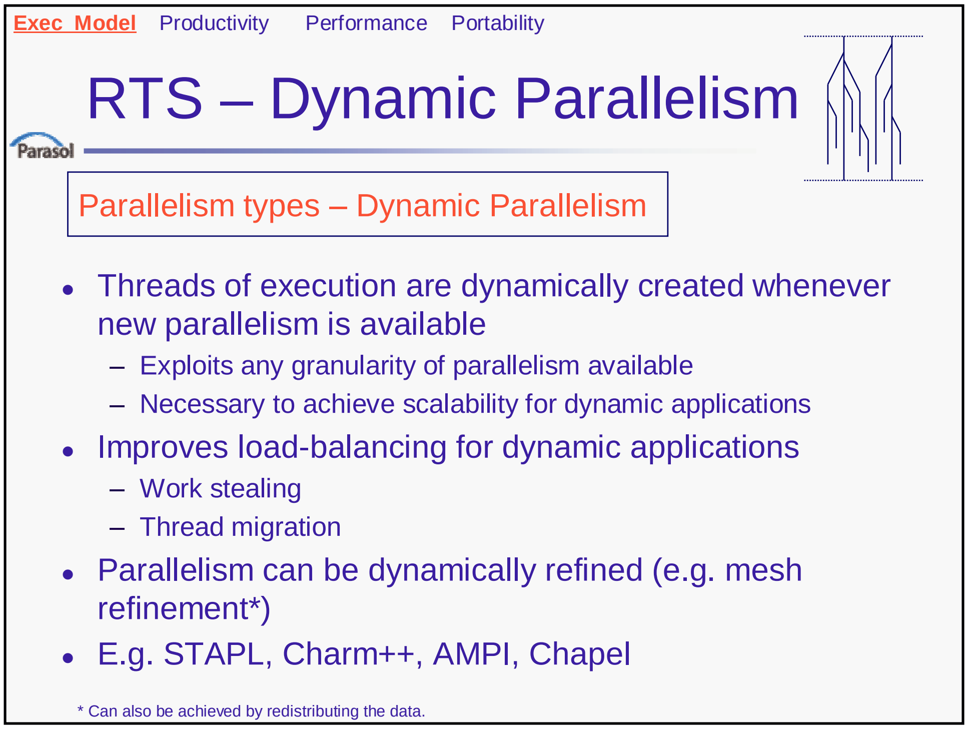
RTS – Nested Parallelism



Parallelism types – Nested Parallelism

- Parallelism is hierarchal
  - Threads of execution can spawn new threads to execute their task
  - Exploits multiple levels of parallelism (e.g. nested parallel loops)
- Good affinity with heterogeneous architectures (e.g. clusters of SMPs)*
  - Allows the exploitation of different levels of granularity
- Natural fit for composed parallel data structures*
  - E.g. `p_vector< p_list< Type > >`
- E.g. OpenMP, Cilk, TBB

* Also for dynamic parallelism.



Exec Model Productivity Performance Portability

RTS – Dynamic Parallelism

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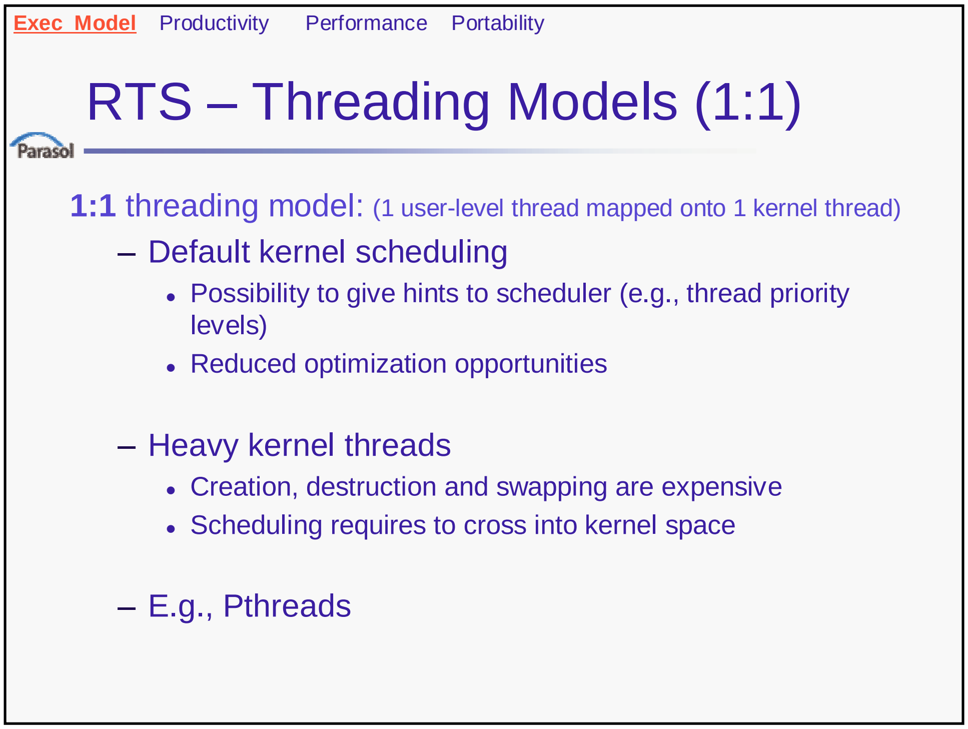
Parallelism types – Dynamic Parallelism

- Threads of execution are dynamically created whenever new parallelism is available
  - Exploits any granularity of parallelism available
  - Necessary to achieve scalability for dynamic applications
- Improves load-balancing for dynamic applications
  - Work stealing
  - Thread migration
- Parallelism can be dynamically refined (e.g. mesh refinement*)
- E.g. STAPL, Charm++, AMPI, Chapel

* Can also be achieved by redistributing the data.



Exec Model Productivity Performance Portability

RTS – Threading Models (1:1)

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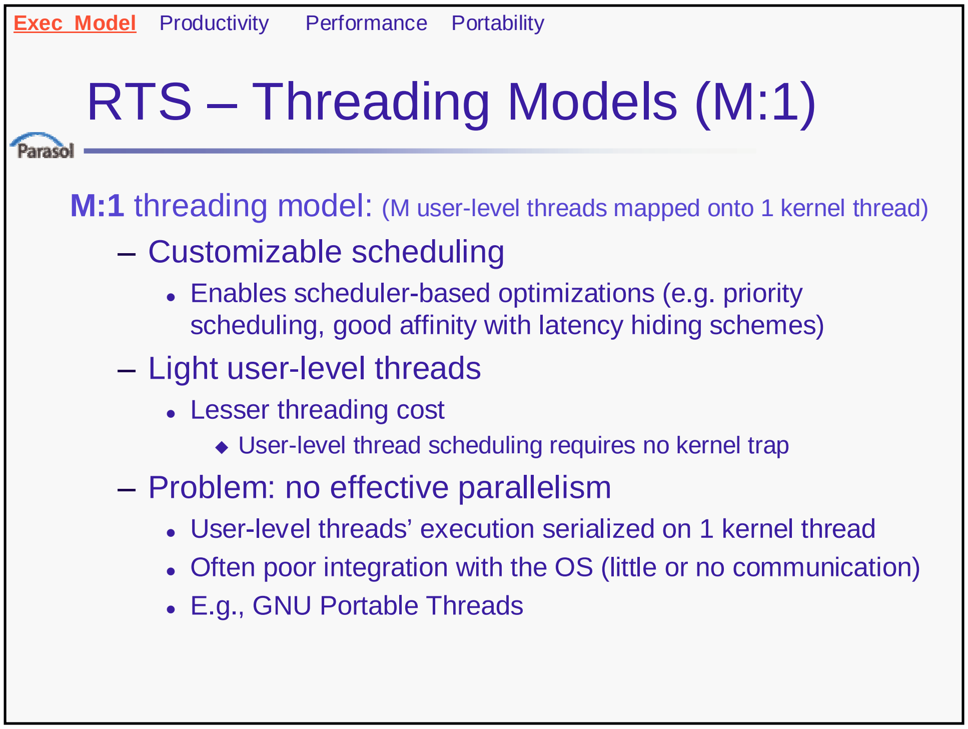
1:1 threading model: (1 user-level thread mapped onto 1 kernel thread)

- Default kernel scheduling
  - Possibility to give hints to scheduler (e.g., thread priority levels)
  - Reduced optimization opportunities
- Heavy kernel threads
  - Creation, destruction and swapping are expensive
  - Scheduling requires to cross into kernel space
- E.g., Pthreads

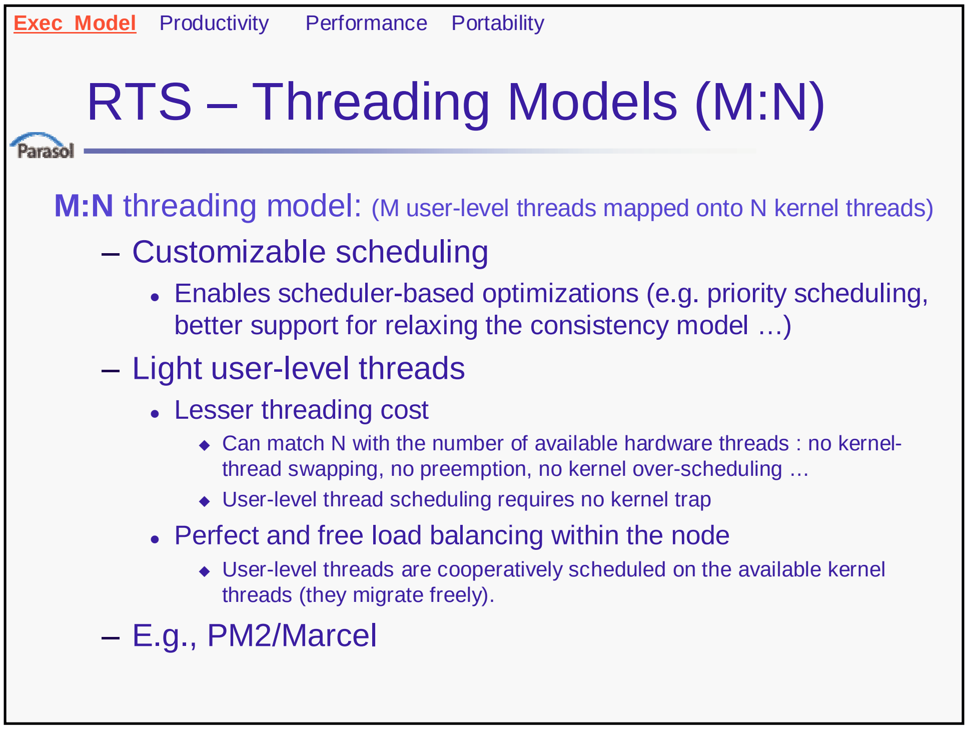


Exec Model Productivity Performance Portability

RTS – Threading Models (M:1)

M:1 threading model: (M user-level threads mapped onto 1 kernel thread)

- Customizable scheduling
  - Enables scheduler-based optimizations (e.g. priority scheduling, good affinity with latency hiding schemes)
- Light user-level threads
  - Lesser threading cost
    - User-level thread scheduling requires no kernel trap
- Problem: no effective parallelism
  - User-level threads' execution serialized on 1 kernel thread
  - Often poor integration with the OS (little or no communication)
  - E.g., GNU Portable Threads

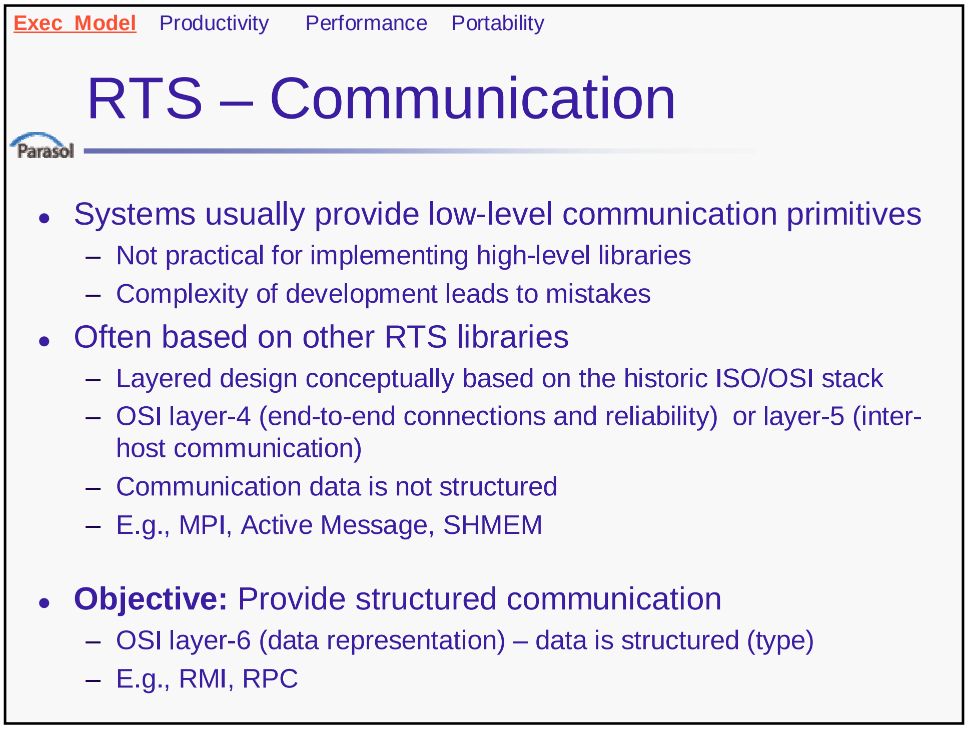


Exec Model Productivity Performance Portability

RTS – Threading Models (M:N)

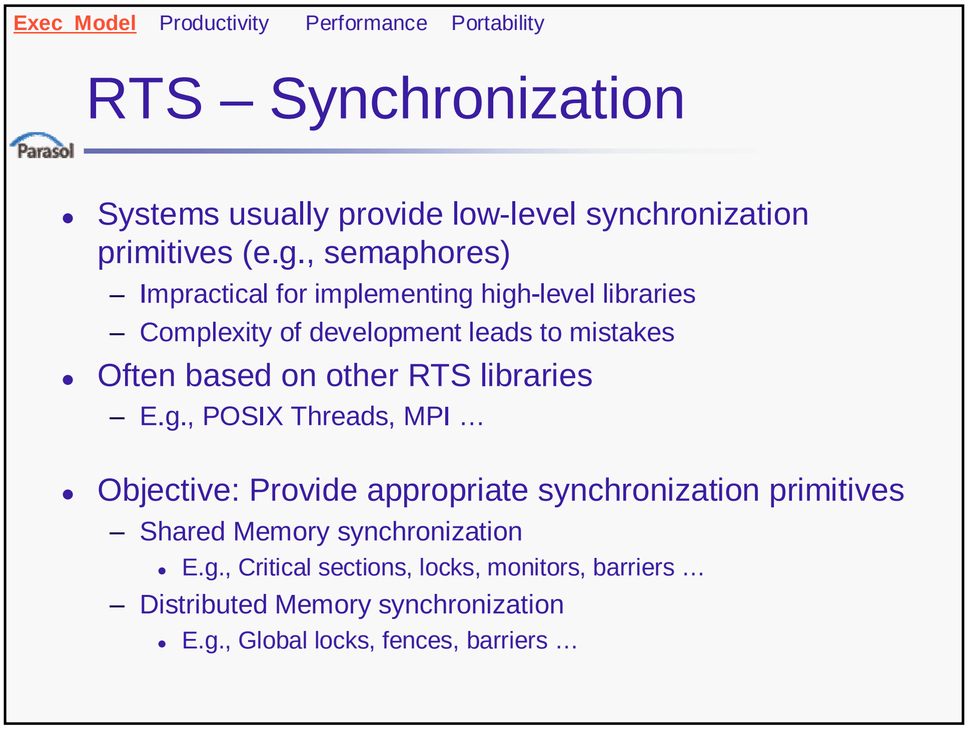
M:N threading model: (M user-level threads mapped onto N kernel threads)

- Customizable scheduling
  - Enables scheduler-based optimizations (e.g. priority scheduling, better support for relaxing the consistency model …)
- Light user-level threads
  - Lesser threading cost
    - Can match N with the number of available hardware threads : no kernel-thread swapping, no preemption, no kernel over-scheduling …
    - User-level thread scheduling requires no kernel trap
  - Perfect and free load balancing within the node
    - User-level threads are cooperatively scheduled on the available kernel threads (they migrate freely).
- E.g., PM2/Marcel



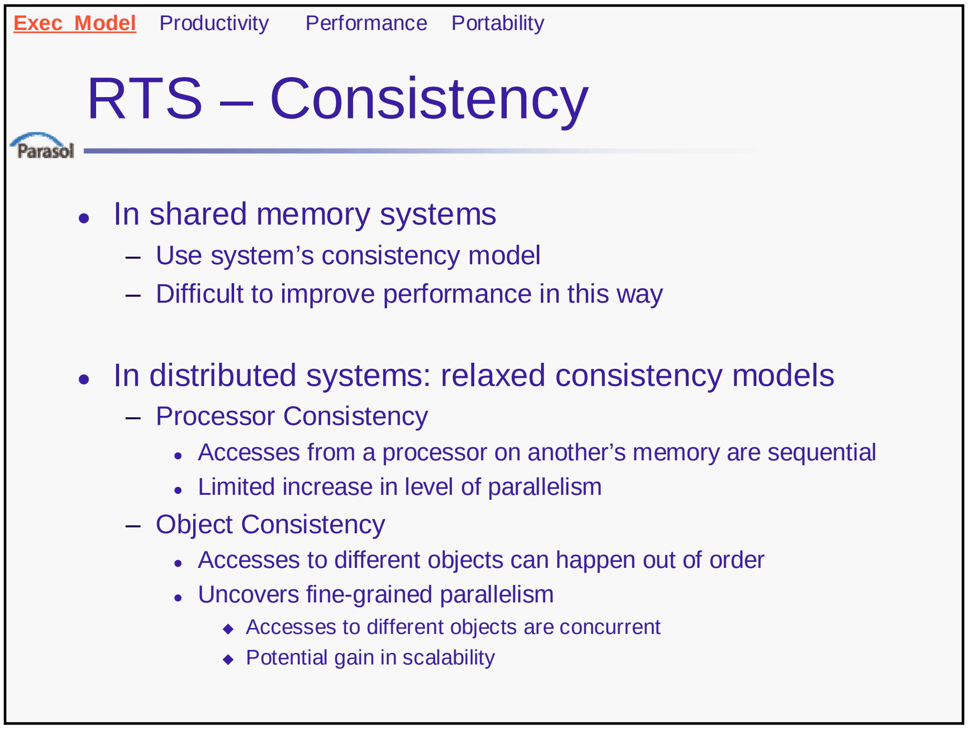
RTS – Communication

- Systems usually provide low-level communication primitives
  - Not practical for implementing high-level libraries
  - Complexity of development leads to mistakes
- Often based on other RTS libraries
  - Layered design conceptually based on the historic ISO/OSI stack
  - OSI layer-4 (end-to-end connections and reliability) or layer-5 (inter-host communication)
  - Communication data is not structured
  - E.g., MPI, Active Message, SHMEM
- **Objective:** Provide structured communication
  - OSI layer-6 (data representation) – data is structured (type)
  - E.g., RMI, RPC



RTS – Synchronization

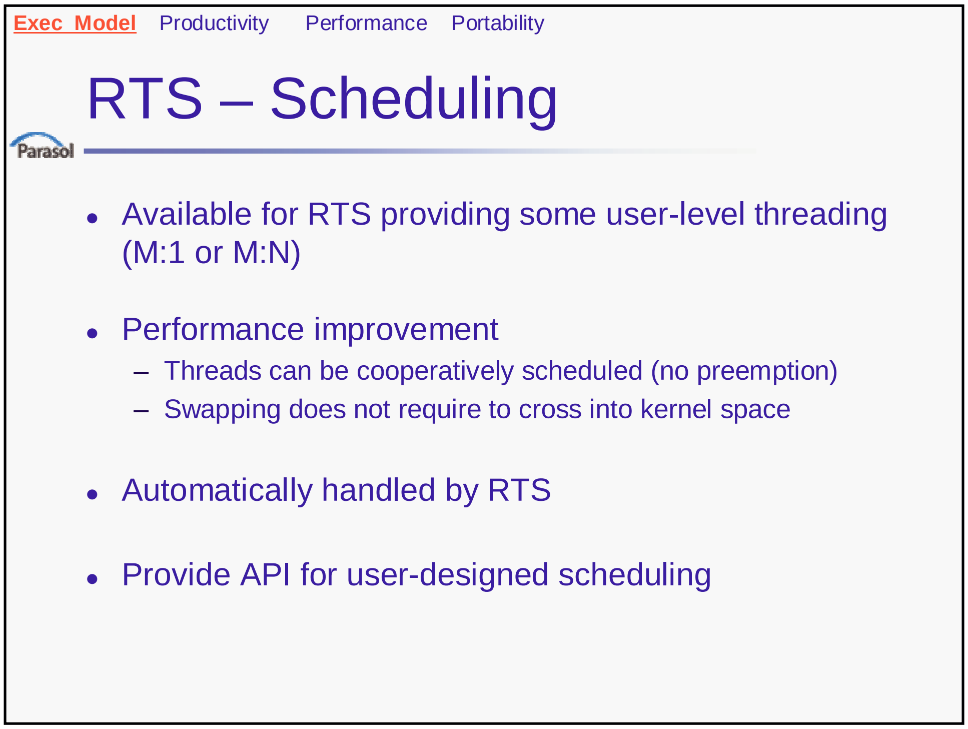
- Systems usually provide low-level synchronization primitives (e.g., semaphores)
  - Impractical for implementing high-level libraries
  - Complexity of development leads to mistakes
- Often based on other RTS libraries
  - E.g., POSIX Threads, MPI …
- Objective: Provide appropriate synchronization primitives
  - Shared Memory synchronization
    - E.g., Critical sections, locks, monitors, barriers …
  - Distributed Memory synchronization
    - E.g., Global locks, fences, barriers …



Exec Model Productivity Performance Portability

RTS – Consistency

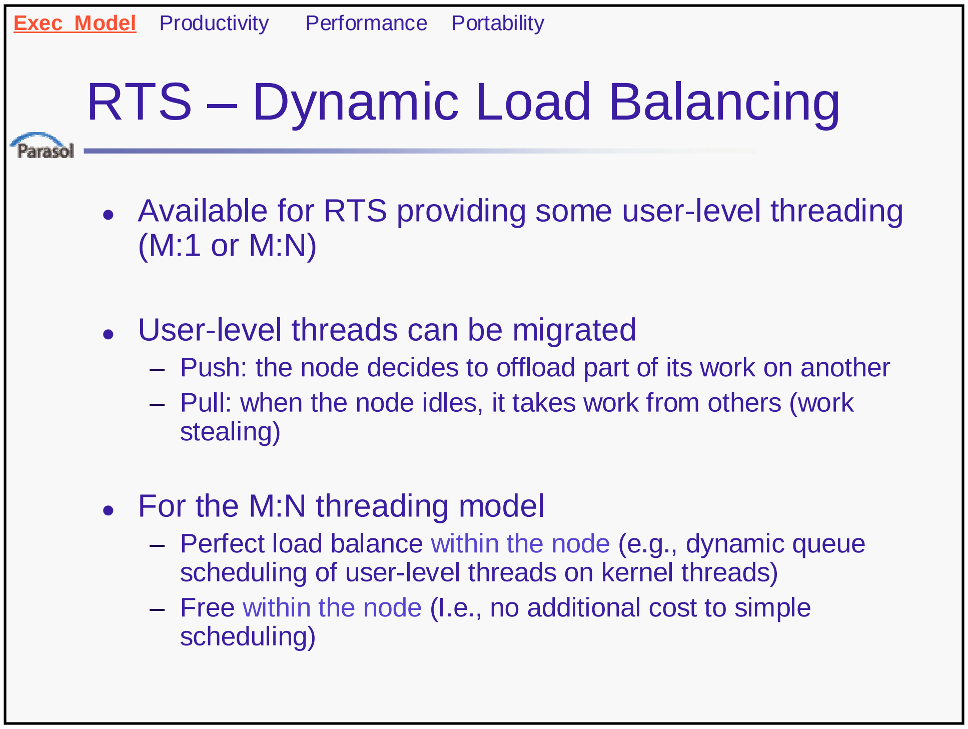
- In shared memory systems
  - Use system's consistency model
  - Difficult to improve performance in this way
- In distributed systems: relaxed consistency models
  - Processor Consistency
    - Accesses from a processor on another's memory are sequential
    - Limited increase in level of parallelism
  - Object Consistency
    - Accesses to different objects can happen out of order
    - Uncovers fine-grained parallelism
      - Accesses to different objects are concurrent
      - Potential gain in scalability



Exec Model Productivity Performance Portability

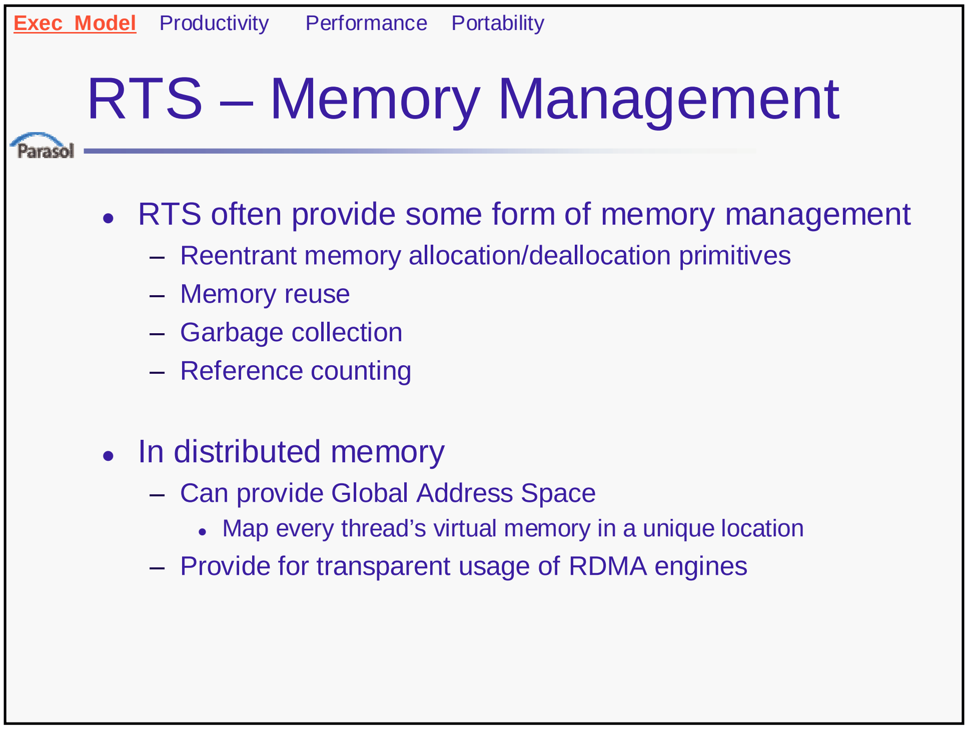
RTS – Scheduling

- Available for RTS providing some user-level threading (M:1 or M:N)
- Performance improvement
  - Threads can be cooperatively scheduled (no preemption)
  - Swapping does not require to cross into kernel space
- Automatically handled by RTS
- Provide API for user-designed scheduling



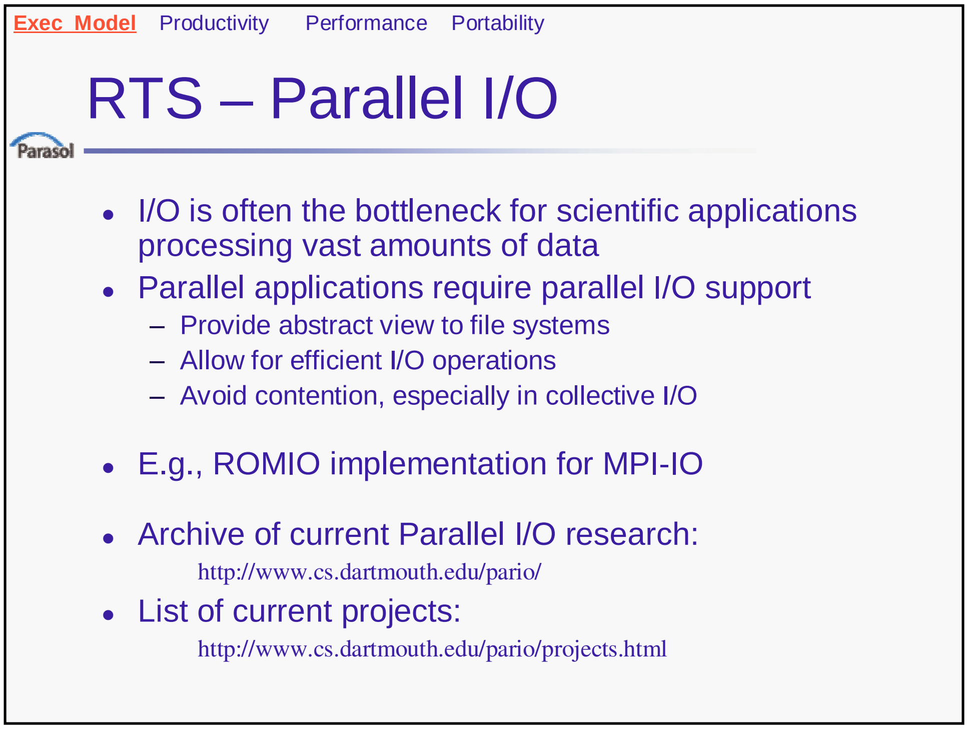
RTS – Dynamic Load Balancing

- Available for RTS providing some user-level threading (M:1 or M:N)
- User-level threads can be migrated
  - Push: the node decides to offload part of its work on another
  - Pull: when the node idles, it takes work from others (work stealing)
- For the M:N threading model
  - Perfect load balance within the node (e.g., dynamic queue scheduling of user-level threads on kernel threads)
  - Free within the node (I.e., no additional cost to simple scheduling)



RTS – Memory Management

- RTS often provide some form of memory management
  - Reentrant memory allocation/deallocation primitives
  - Memory reuse
  - Garbage collection
  - Reference counting
- In distributed memory
  - Can provide Global Address Space
    - Map every thread's virtual memory in a unique location
  - Provide for transparent usage of RDMA engines



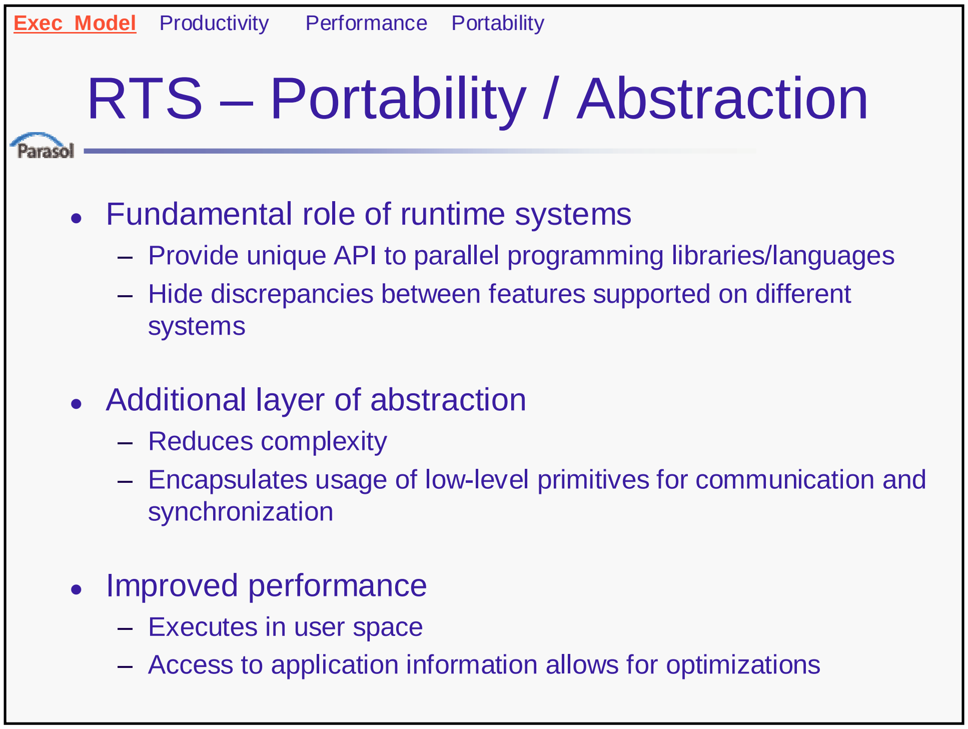
RTS – Parallel I/O

Parasol

- I/O is often the bottleneck for scientific applications processing vast amounts of data
- Parallel applications require parallel I/O support
  - Provide abstract view to file systems
  - Allow for efficient I/O operations
  - Avoid contention, especially in collective I/O
- E.g., ROMIO implementation for MPI-IO
- Archive of current Parallel I/O research:

  http://www.cs.dartmouth.edu/pario/
- List of current projects:

  http://www.cs.dartmouth.edu/pario/projects.html



RTS – Portability / Abstraction

Parasol

- Fundamental role of runtime systems
  - Provide unique API to parallel programming libraries/languages
  - Hide discrepancies between features supported on different systems
- Additional layer of abstraction
  - Reduces complexity
  - Encapsulates usage of low-level primitives for communication and synchronization
- Improved performance
  - Executes in user space
  - Access to application information allows for optimizations

Exec Model Productivity Performance Portability

References

Parasol

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  - Performance
  - Portability
- Shared Memory Programming
- Message Passing Programming
- Shared Memory Models
- PGAS Languages
- Other Programming Models

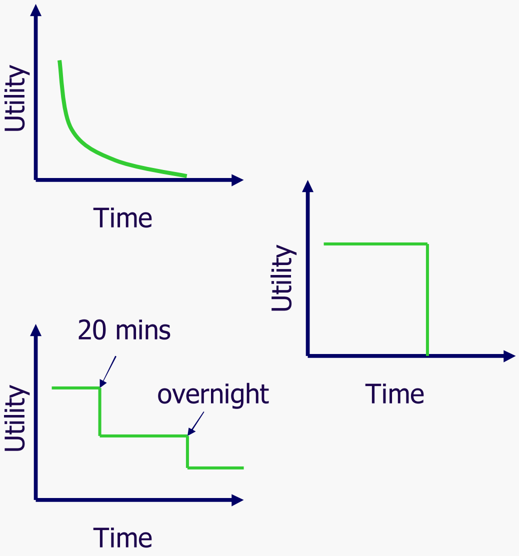
Productivity

- Reduce time to solution
  - Programming time + execution time
- Reduce cost of solution
- Function of:
  - problem solved *P*
  - system used *S*
  - Utility function *U*

$$\Psi = \Psi(P, S, U)$$

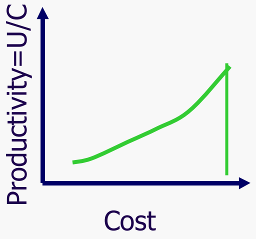
Utility Functions

- Decreasing in time.
- Extreme example: deadline driven
- Practical approximation: staircase



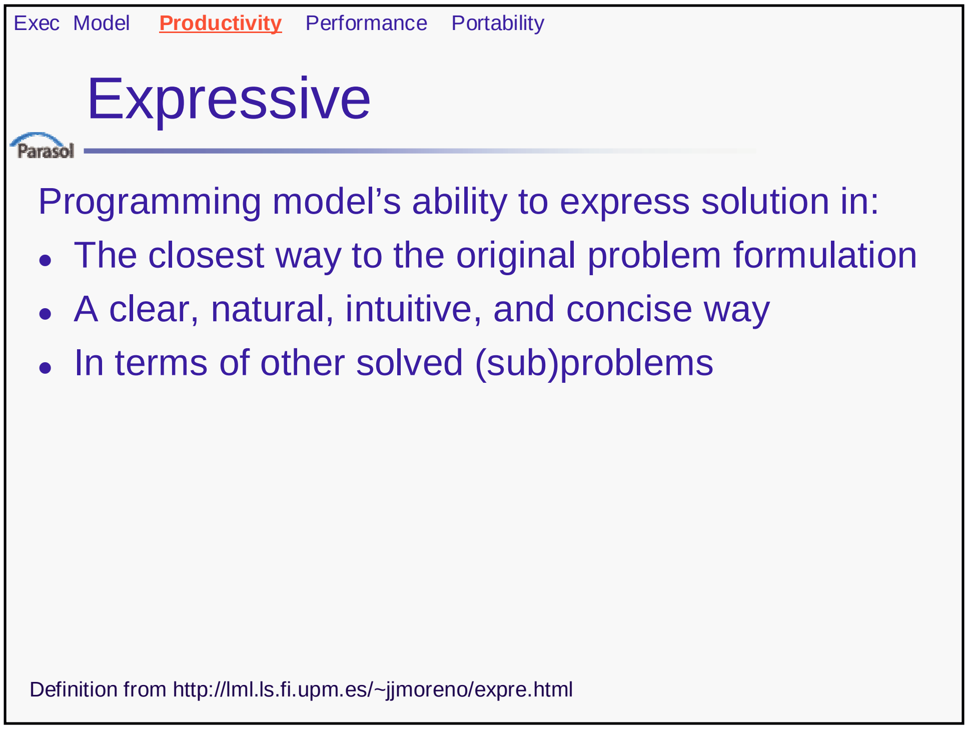
Simple Example

- Assume deadline-driven Utility and decreasing Cost
- Max productivity achieved by solving problem just fast enough to match deadline
- Need to account for uncertainty



Programming Model Impact

- Features try to reduce development time
  - Expressiveness
  - Level of abstraction
  - Component Reuse
  - Expandability
  - Base language
  - Debugging capability
  - Tuning capability
  - Machine model
  - Interoperability with other languages
- Impact on performance examined separately



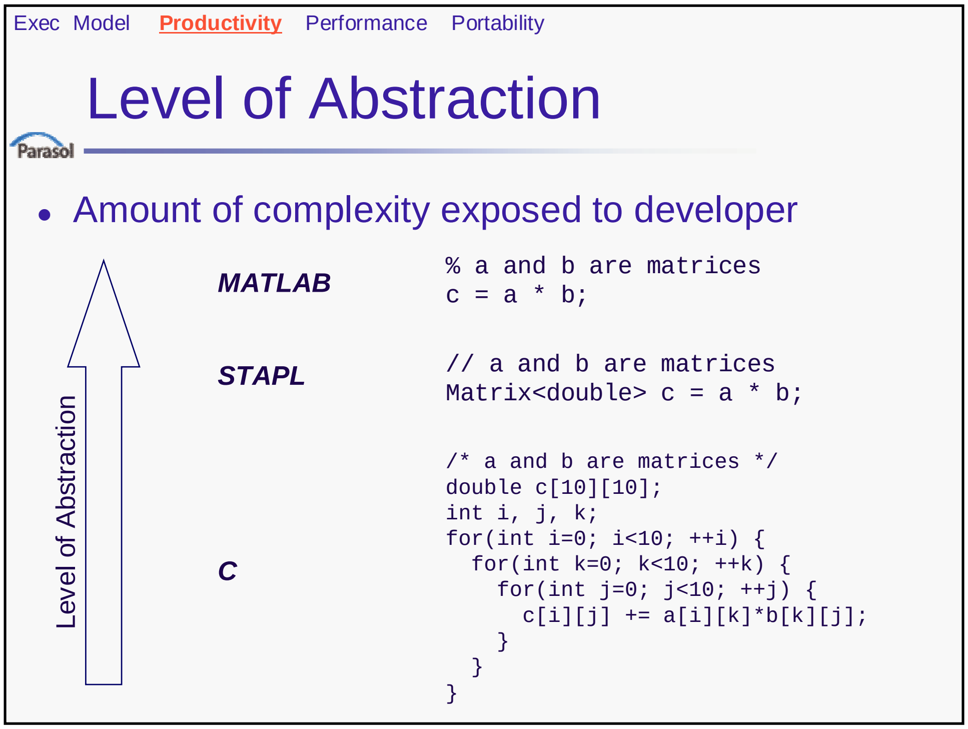
Expressive

Parasol

Programming model's ability to express solution in:

- The closest way to the original problem formulation
- A clear, natural, intuitive, and concise way
- In terms of other solved (sub)problems

Definition from http://lml.ls.fi.upm.es/~jjmoreno/expre.html



Level of Abstraction

Parasol

- Amount of complexity exposed to developer

Level of Abstraction

MATLAB

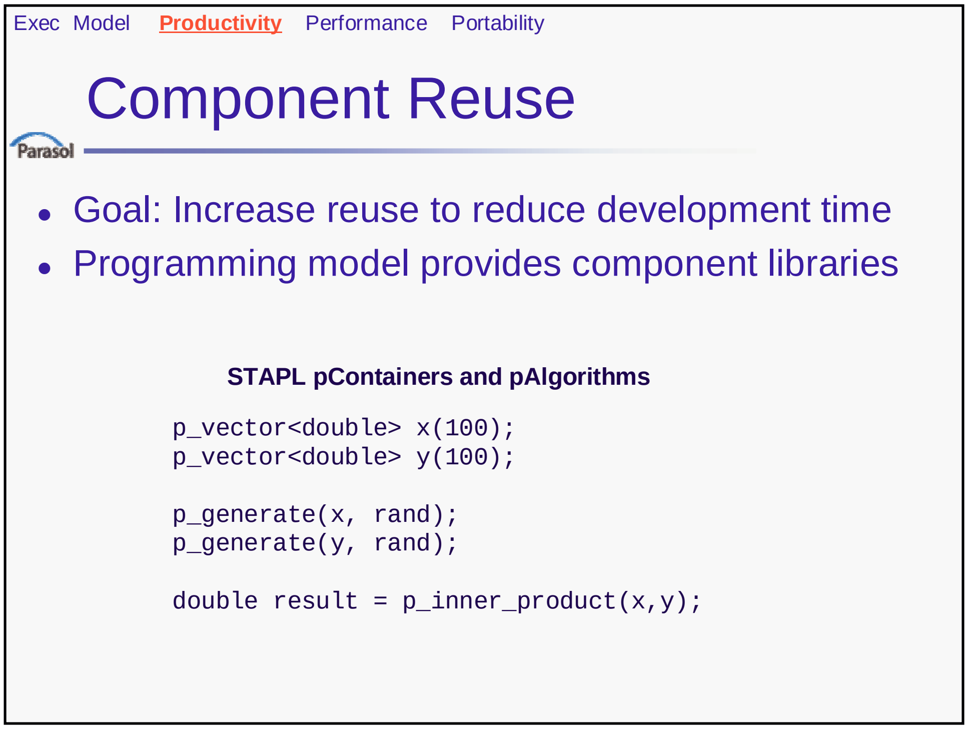
```
% a and b are matrices
c = a * b;
```

STAPL

```
// a and b are matrices
Matrix<double> c = a * b;
```

C

```
/* a and b are matrices */
double c[10][10];
int i, j, k;
for(int i=0; i<10; ++i) {
  for(int k=0; k<10; ++k) {
    for(int j=0; j<10; ++j) {
      c[i][j] += a[i][k]*b[k][j];
    }
  }
}
```



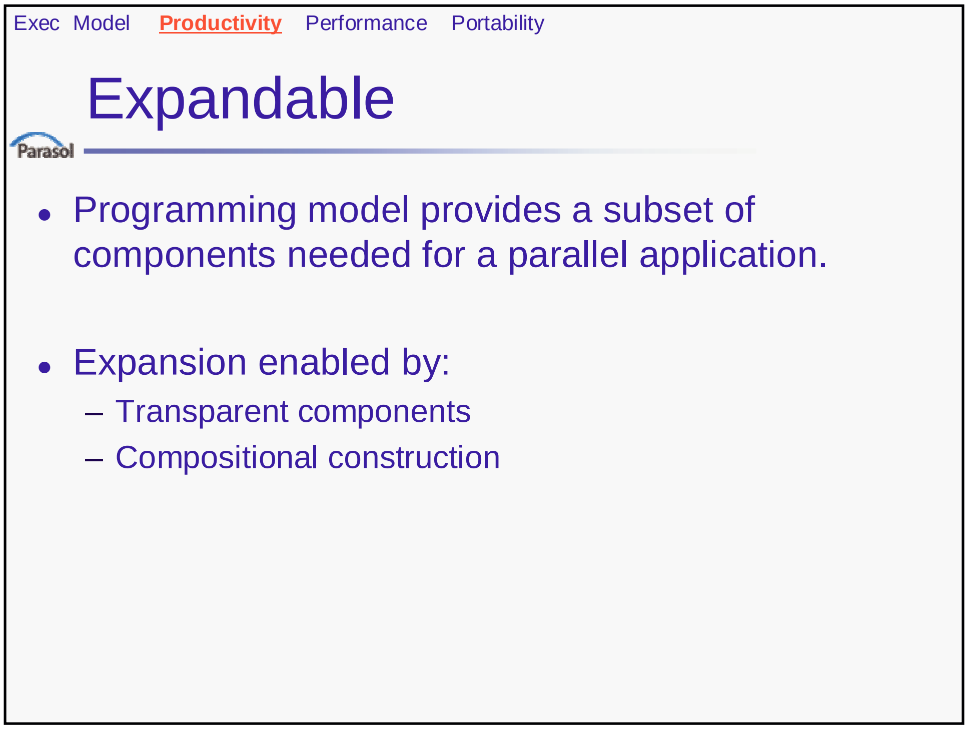
Exec Model **Productivity** Performance Portability

Component Reuse

- Goal: Increase reuse to reduce development time
- Programming model provides component libraries

STAPL pContainers and pAlgorithms

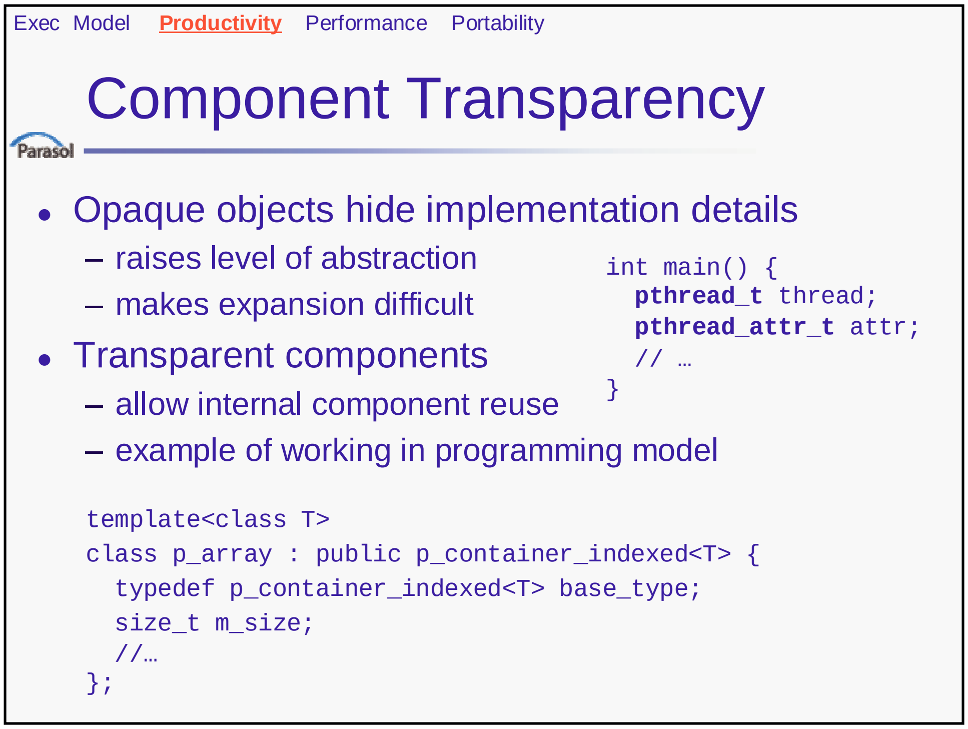
```
p_vector<double> x(100);
p_vector<double> y(100);

p_generate(x, rand);
p_generate(y, rand);

double result = p_inner_product(x,y);
```



Exec Model **Productivity** Performance Portability

Expandable

- Programming model provides a subset of components needed for a parallel application.
- Expansion enabled by:
  - Transparent components
  - Compositional construction



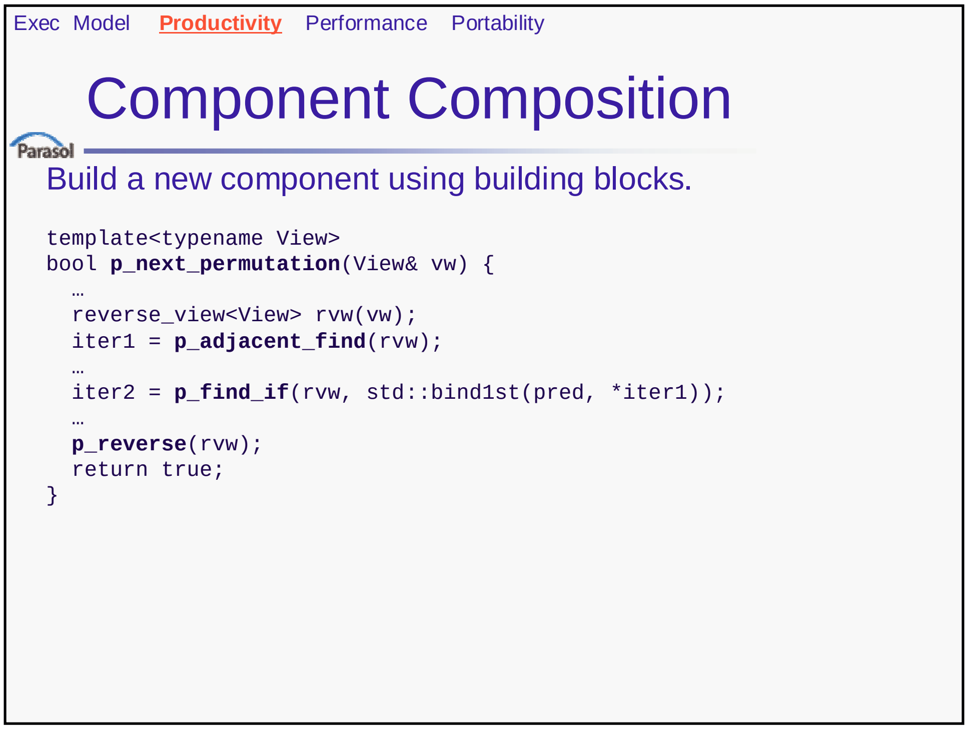
Exec Model **Productivity** Performance Portability

Component Transparency

- Opaque objects hide implementation details
  - raises level of abstraction
  - makes expansion difficult
- Transparent components
  - allow internal component reuse
  - example of working in programming model

```
int main() {
  pthread_t thread;
  pthread_attr_t attr;
  // …
}
```

```
template<class T>
class p_array : public p_container_indexed<T> {
  typedef p_container_indexed<T> base_type;
  size_t m_size;
  //…
};
```

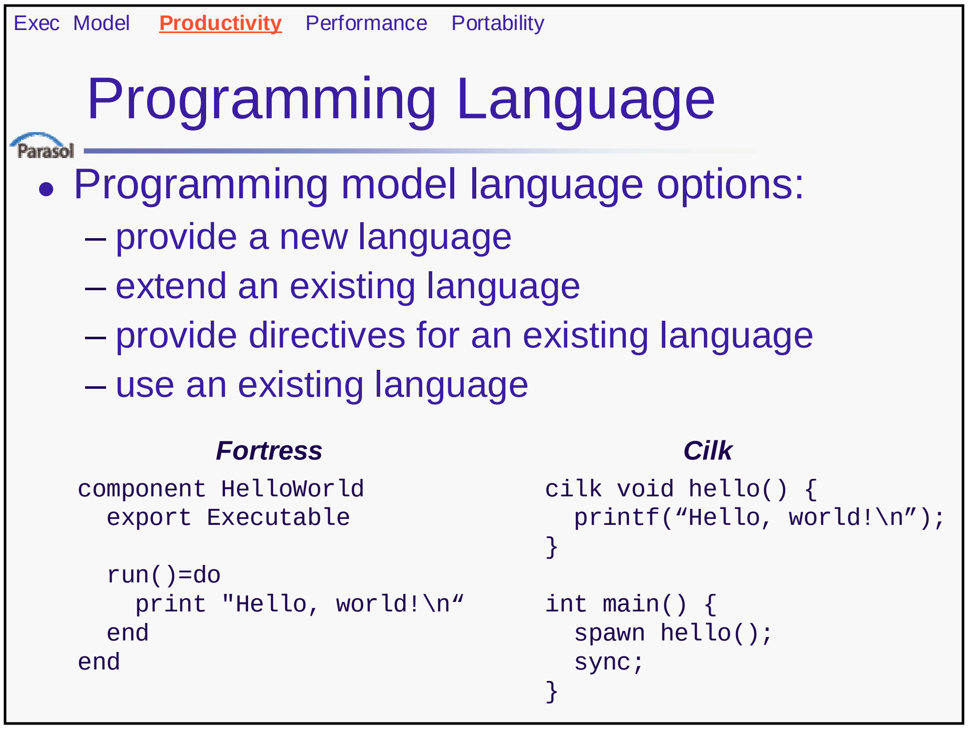


Exec Model **Productivity** Performance Portability

Component Composition

Build a new component using building blocks.

```
template<typename View>
bool p_next_permutation(View& vw) {
  …
  reverse_view<View> rvw(vw);
  iter1 = p_adjacent_find(rvw);
  …
  iter2 = p_find_if(rvw, std::bind1st(pred, *iter1));
  …
  p_reverse(rvw);
  return true;
}
```



Exec Model **Productivity** Performance Portability

Programming Language

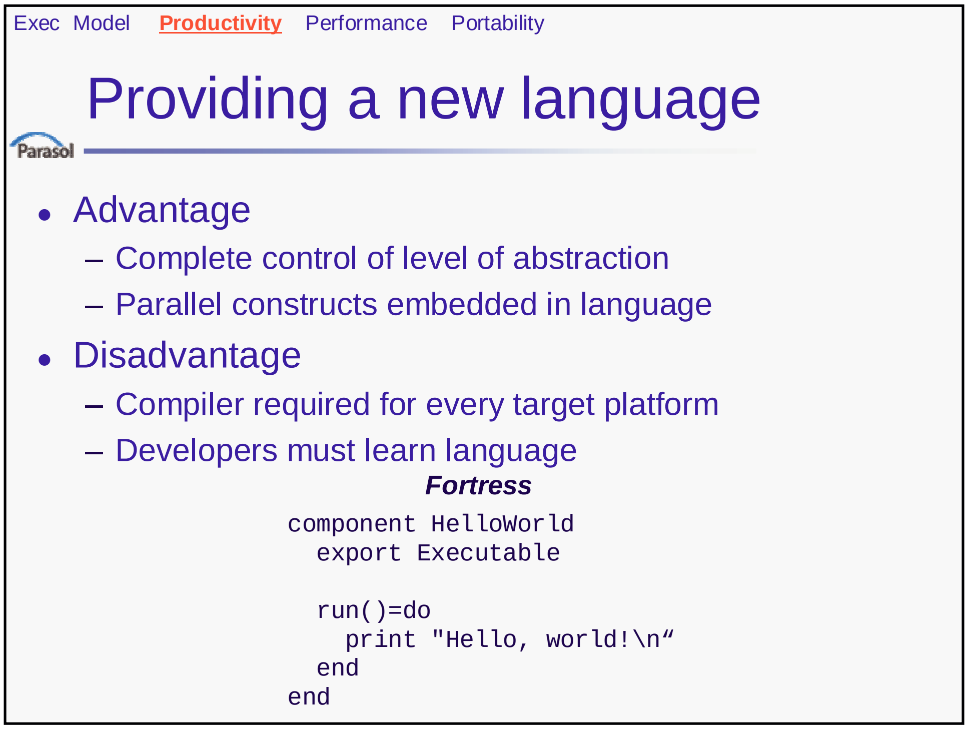
- Programming model language options:
  - provide a new language
  - extend an existing language
  - provide directives for an existing language
  - use an existing language

Fortress

```
component HelloWorld
  export Executable

  run()=do
    print "Hello, world!\n“
  end
end
```

Cilk

```
cilk void hello() {
  printf(“Hello, world!\n”);
}

int main() {
  spawn hello();
  sync;
}
```



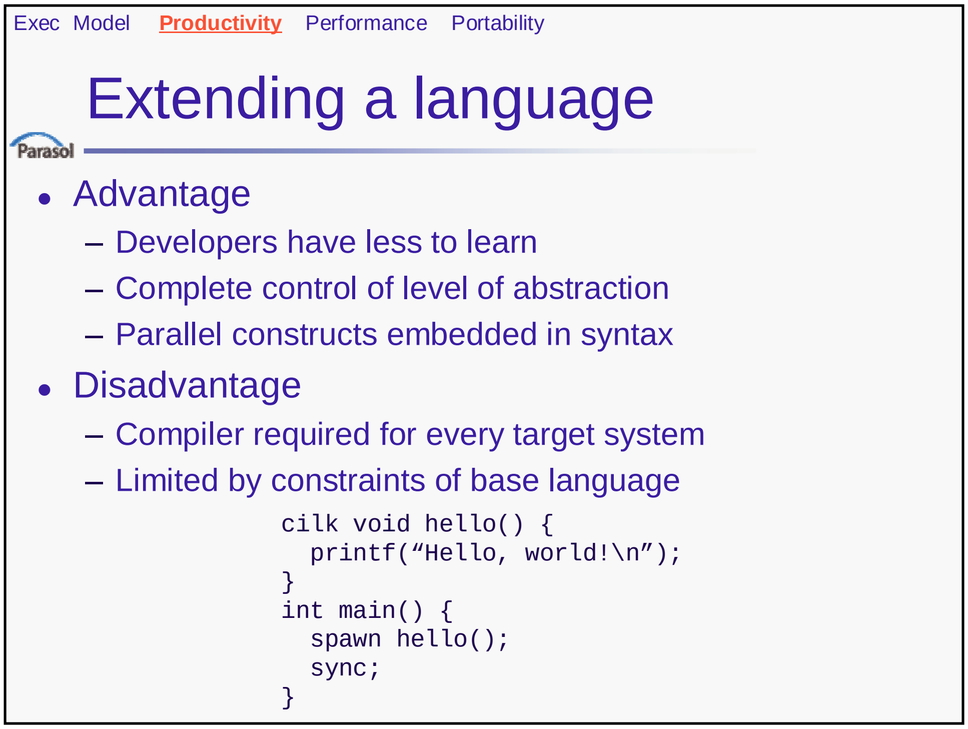
Exec Model **Productivity** Performance Portability

Providing a new language

- Advantage
  - Complete control of level of abstraction
  - Parallel constructs embedded in language
- Disadvantage
  - Compiler required for every target platform
  - Developers must learn language

Fortress

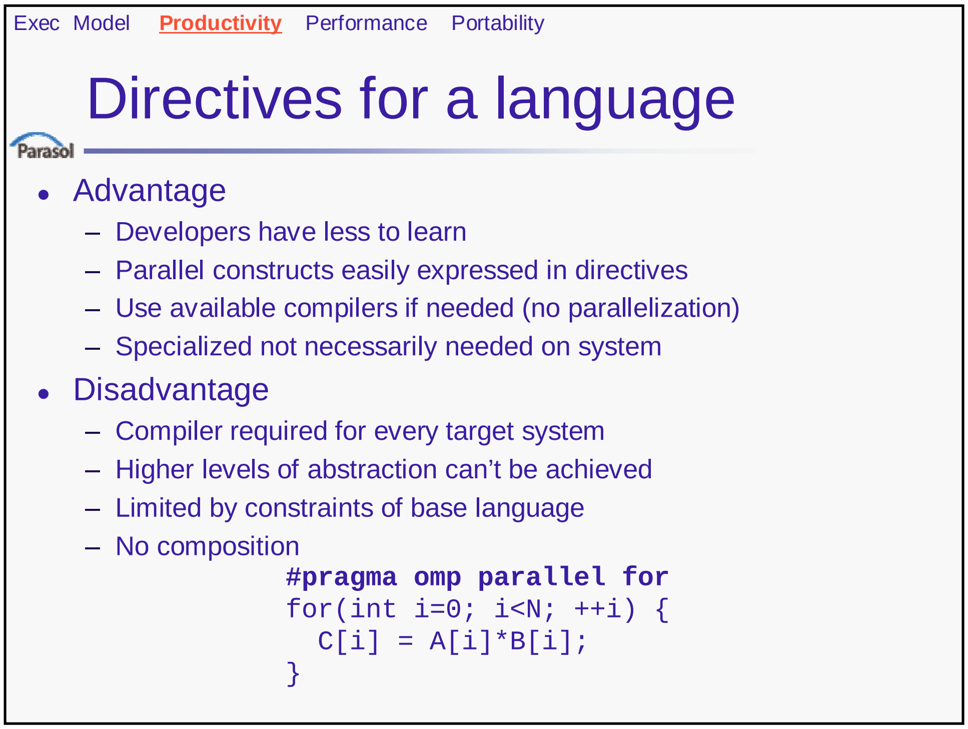
```
component HelloWorld
  export Executable

  run()=do
    print "Hello, world!\n“
  end
end
```



Extending a language

- Advantage
  - Developers have less to learn
  - Complete control of level of abstraction
  - Parallel constructs embedded in syntax
- Disadvantage
  - Compiler required for every target system
  - Limited by constraints of base language

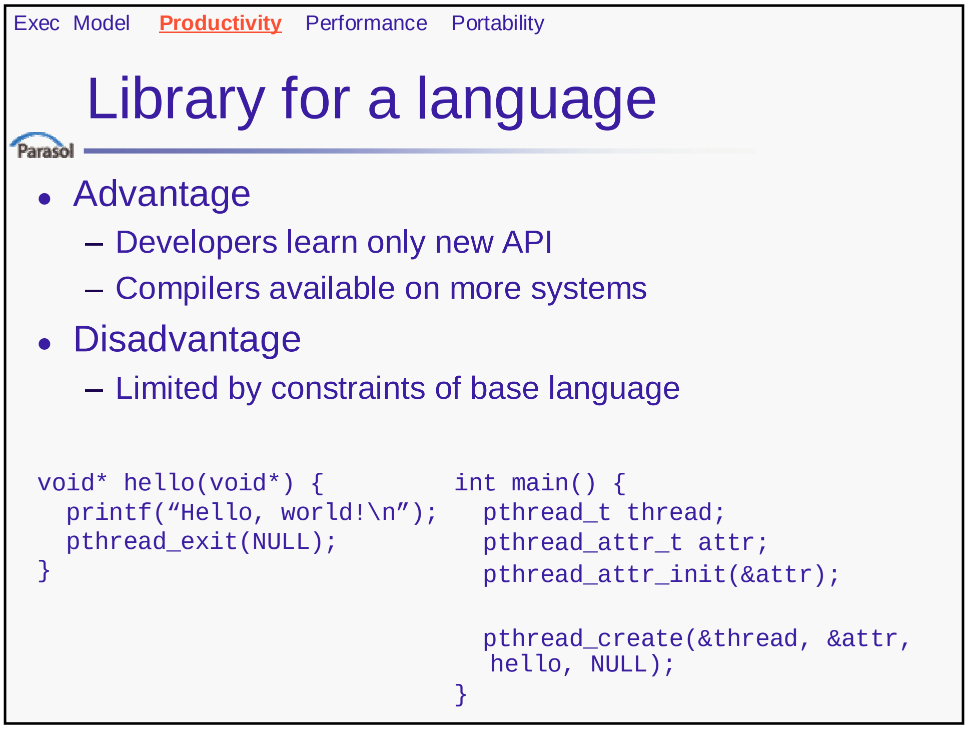
```
cilk void hello() {
  printf(“Hello, world!\n”);
}
int main() {
  spawn hello();
  sync;
}
```



Directives for a language

- Advantage
  - Developers have less to learn
  - Parallel constructs easily expressed in directives
  - Use available compilers if needed (no parallelization)
  - Specialized not necessarily needed on system
- Disadvantage
  - Compiler required for every target system
  - Higher levels of abstraction can’t be achieved
  - Limited by constraints of base language
  - No composition

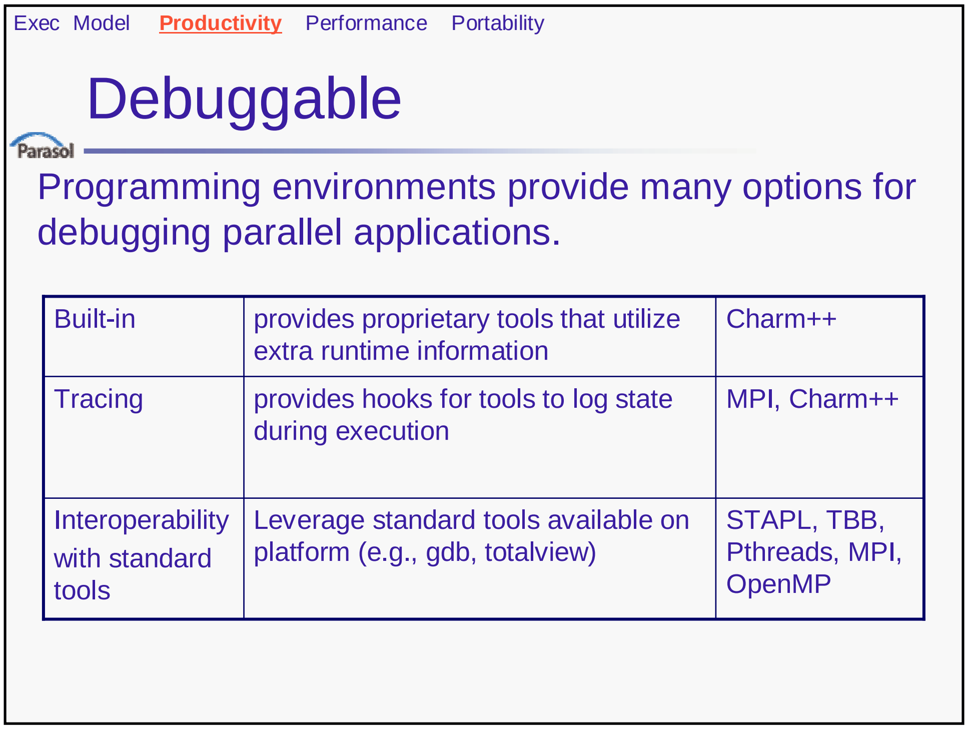
```
#pragma omp parallel for
for(int i=0; i<N; ++i) {
  C[i] = A[i]*B[i];
}
```



Library for a language

- Advantage
  - Developers learn only new API
  - Compilers available on more systems
- Disadvantage
  - Limited by constraints of base language

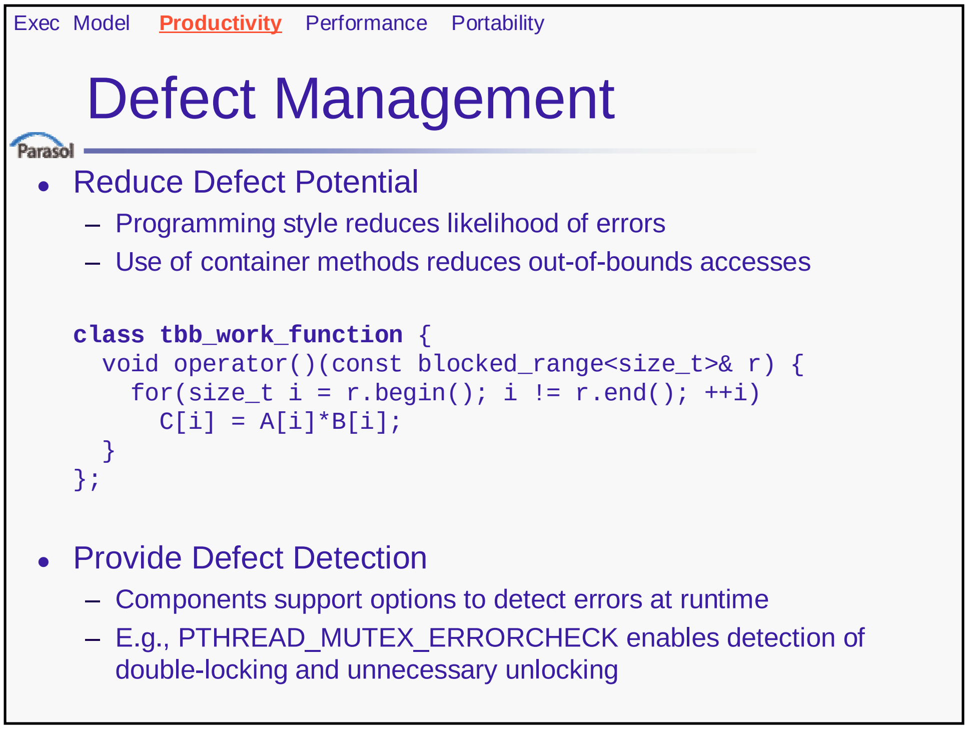
```
void* hello(void*) {          int main() {
  printf("Hello, world!\n");    pthread_t thread;
  pthread_exit(NULL);           pthread_attr_t attr;
}                               pthread_attr_init(&attr);

                                pthread_create(&thread, &attr,
                                 hello, NULL);
                              }
```



Debuggable

Programming environments provide many options for debugging parallel applications.

Built-in	provides proprietary tools that utilize extra runtime information	Charm++
Tracing	provides hooks for tools to log state during execution	MPI, Charm++
Interoperability with standard tools	Leverage standard tools available on platform (e.g., gdb, totalview)	STAPL, TBB, Pthreads, MPI, OpenMP



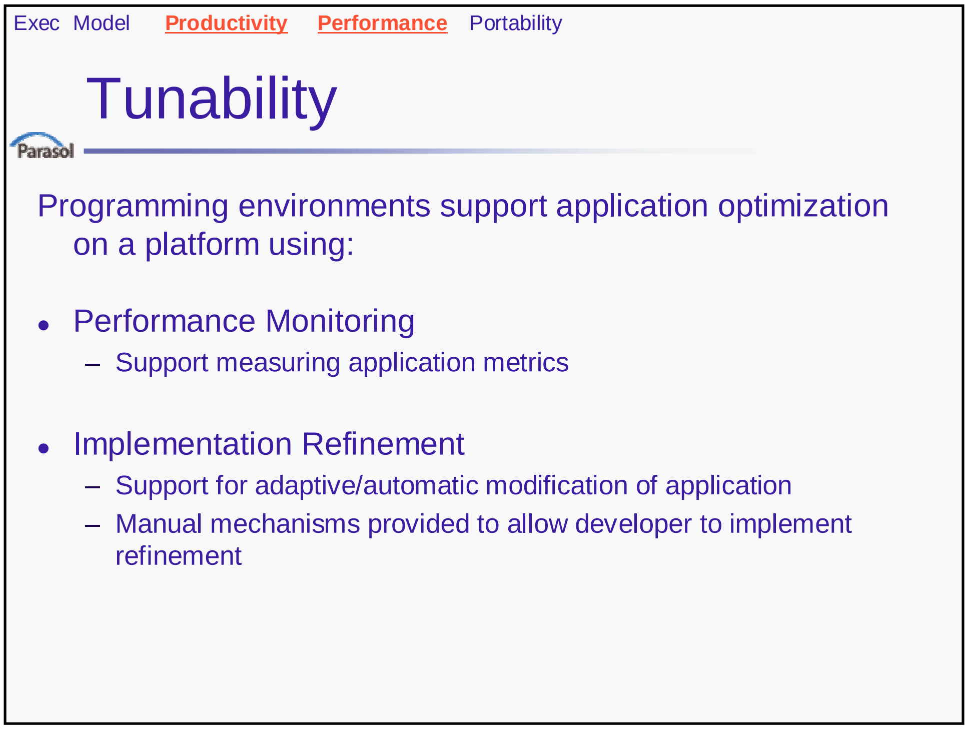
Exec Model **Productivity** Performance Portability

Defect Management

- Reduce Defect Potential
  - Programming style reduces likelihood of errors
  - Use of container methods reduces out-of-bounds accesses

```
class tbb_work_function {
  void operator()(const blocked_range<size_t>& r) {
    for(size_t i = r.begin(); i != r.end(); ++i)
      C[i] = A[i]*B[i];
  }
};
```

- Provide Defect Detection
  - Components support options to detect errors at runtime
  - E.g., PTHREAD_MUTEX_ERRORCHECK enables detection of double-locking and unnecessary unlocking

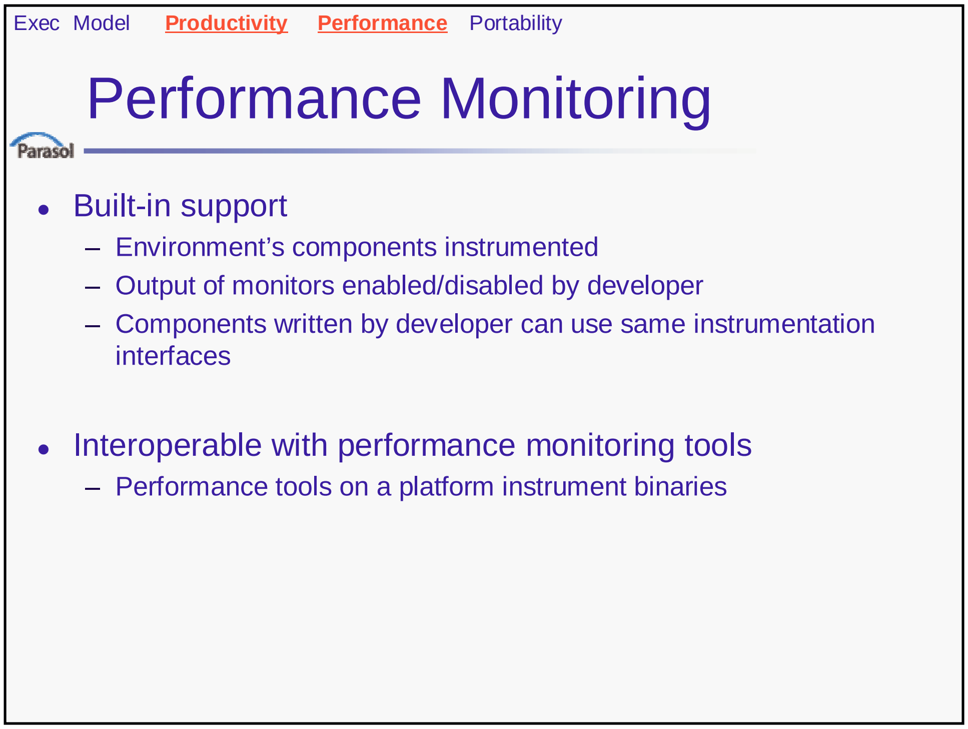


Exec Model **Productivity** **Performance** Portability

Tunability

Programming environments support application optimization on a platform using:

- Performance Monitoring
  - Support measuring application metrics
- Implementation Refinement
  - Support for adaptive/automatic modification of application
  - Manual mechanisms provided to allow developer to implement refinement

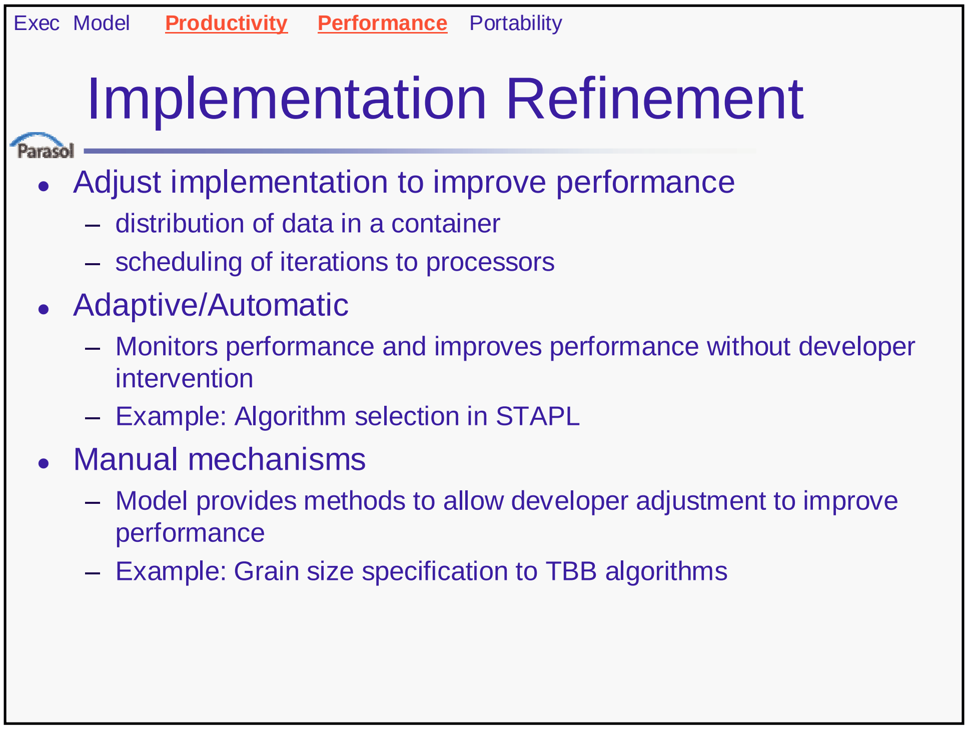


Exec Model **Productivity** **Performance** Portability

Performance Monitoring

Parasol

- Built-in support
  - Environment’s components instrumented
  - Output of monitors enabled/disabled by developer
  - Components written by developer can use same instrumentation interfaces
- Interoperable with performance monitoring tools
  - Performance tools on a platform instrument binaries

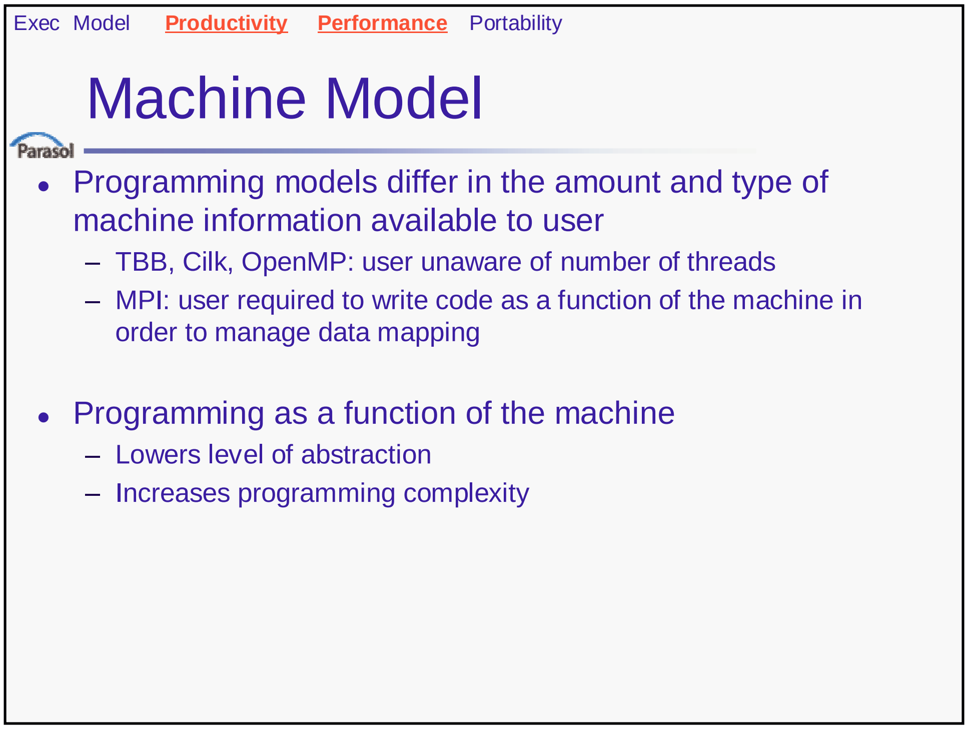


Exec Model **Productivity** **Performance** Portability

Implementation Refinement

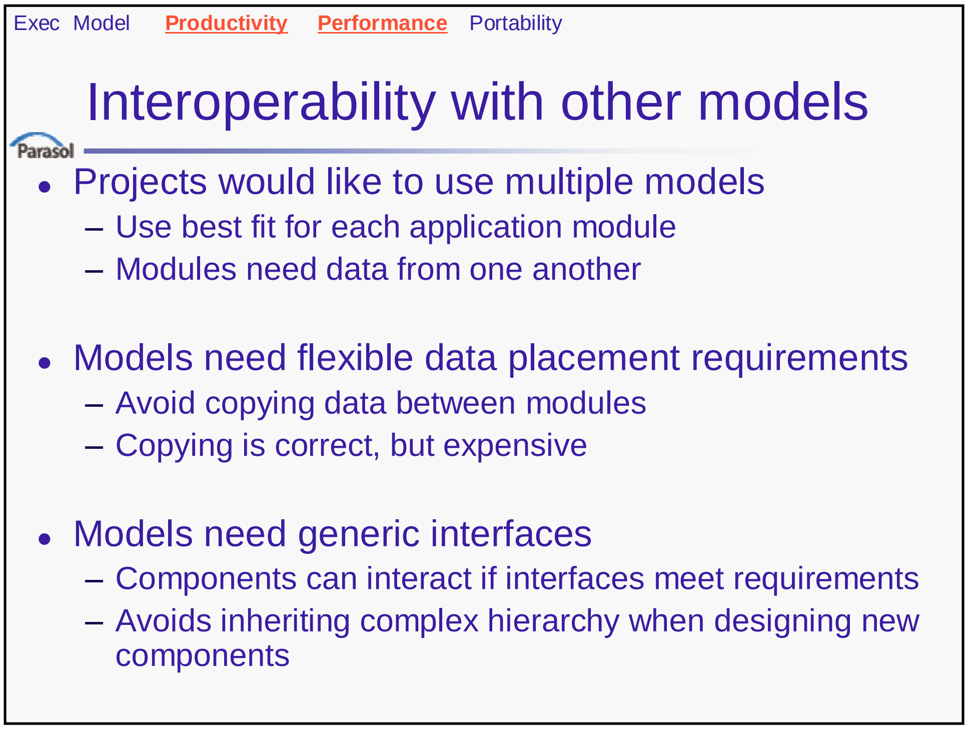
Parasol

- Adjust implementation to improve performance
  - distribution of data in a container
  - scheduling of iterations to processors
- Adaptive/Automatic
  - Monitors performance and improves performance without developer intervention
  - Example: Algorithm selection in STAPL
- Manual mechanisms
  - Model provides methods to allow developer adjustment to improve performance
  - Example: Grain size specification to TBB algorithms



Machine Model

- Programming models differ in the amount and type of machine information available to user
  - TBB, Cilk, OpenMP: user unaware of number of threads
  - MPI: user required to write code as a function of the machine in order to manage data mapping
- Programming as a function of the machine
  - Lowers level of abstraction
  - Increases programming complexity



Interoperability with other models

- Projects would like to use multiple models
  - Use best fit for each application module
  - Modules need data from one another
- Models need flexible data placement requirements
  - Avoid copying data between modules
  - Copying is correct, but expensive
- Models need generic interfaces
  - Components can interact if interfaces meet requirements
  - Avoids inheriting complex hierarchy when designing new components

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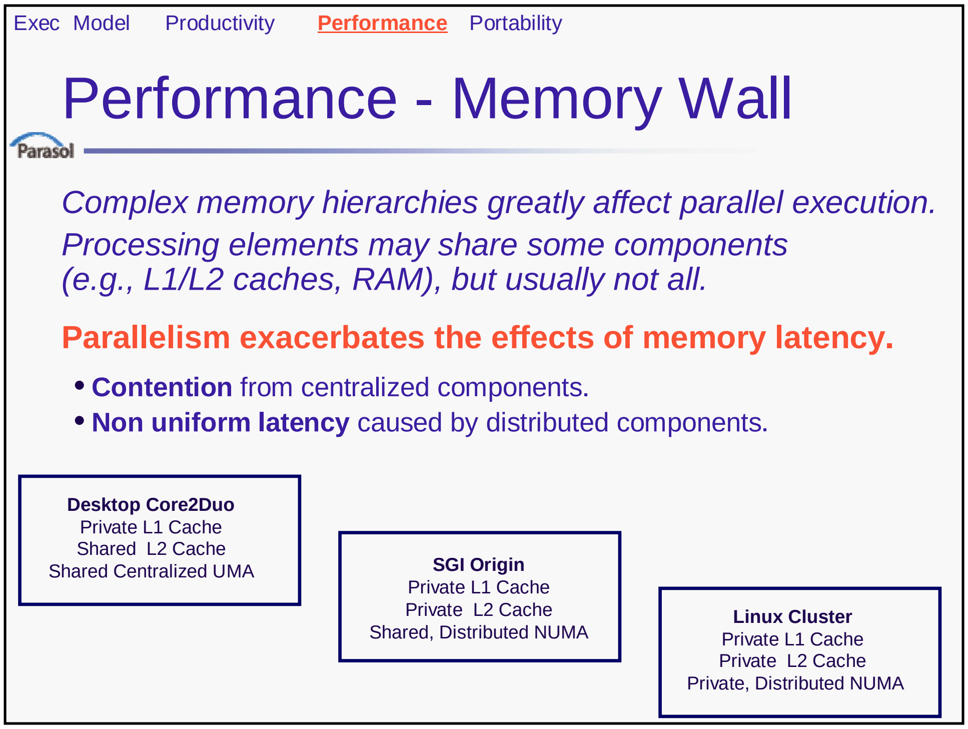
Exec Model Productivity **Performance** Portability

Performance

- Latency Management
- Load Balancing
- Creating a High Degree of Parallelism



Exec Model Productivity **Performance** Portability

Performance - Memory Wall

Complex memory hierarchies greatly affect parallel execution.

Processing elements may share some components (e.g., L1/L2 caches, RAM), but usually not all.

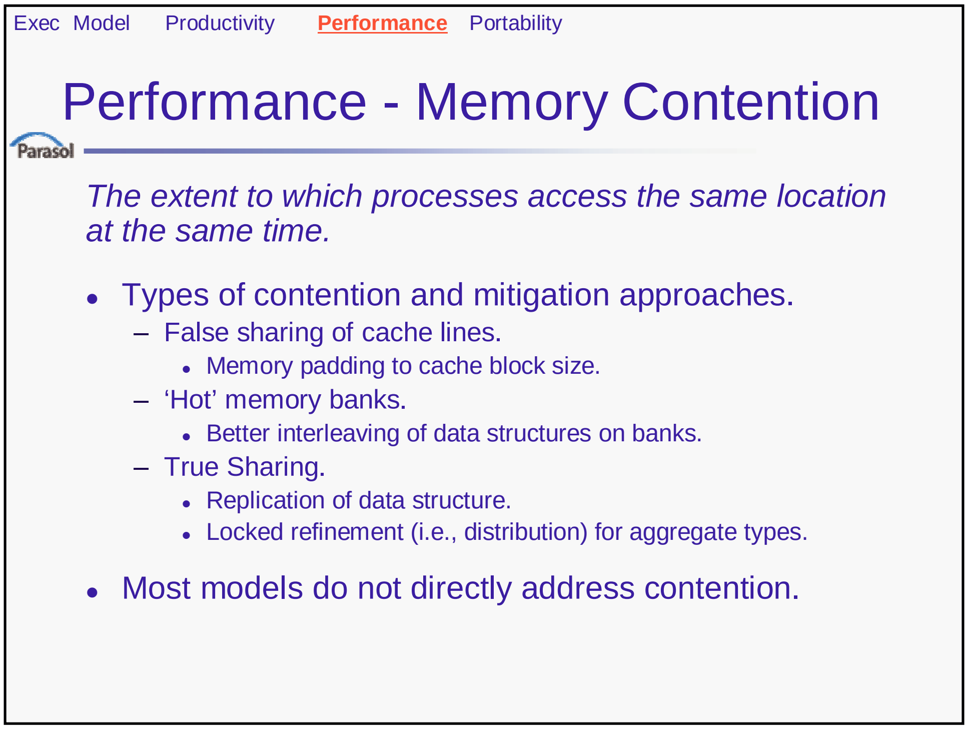
Parallelism exacerbates the effects of memory latency.

- **Contention** from centralized components.
- **Non uniform latency** caused by distributed components.

Desktop Core2Duo
Private L1 Cache
Shared L2 Cache
Shared Centralized UMA

SGI Origin
Private L1 Cache
Private L2 Cache
Shared, Distributed NUMA

Linux Cluster
Private L1 Cache
Private L2 Cache
Private, Distributed NUMA



Exec Model Productivity **Performance** Portability

Performance - Memory Contention

The extent to which processes access the same location at the same time.

- Types of contention and mitigation approaches.
  - False sharing of cache lines.
    - Memory padding to cache block size.
  - ‘Hot’ memory banks.
    - Better interleaving of data structures on banks.
  - True Sharing.
    - Replication of data structure.
    - Locked refinement (i.e., distribution) for aggregate types.
- Most models do not directly address contention.

Performance - Managing Latency

There are two approaches to managing latency.

- Hiding - tolerate latency by overlapping a memory accesses with other computation.
  - User Level
  - Runtime System
- Reducing - minimize latency by having data near the computation that uses it.

Hiding Latency - User Level

Model has programming constructs that allow user to make asynchronous remote requests.

- Split-Phase Execution **(Charm++)**

  Remote requests contain address of return handler.

```
class A {                        class B {
  foo() {                          xyz(Return ret) {
    B b;                             …
    b.xyz(&A::bar());                ret(3);
  }                                }
  bar(int x) { … }               };
};
```

- Futures

  Remote requests create a handle that is later queried.

```
future<double> v(foo());   //thread spawned to execute foo()
…                          //do other unrelated work
double result = v.wait();  //get result of foo()
```

Hiding Latency - Runtime System

Runtime system uses extra parallelism made available to transparently hide latency.

e.g., Multithreading **(STAPL / ARMI)**

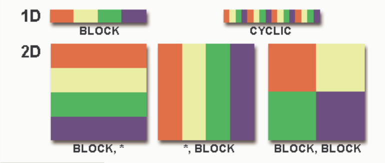
pRange can recursively divide work (based on user defined dependence graph) to increase degree of parallelism. ARMI splits and schedules work into multiple concurrent threads.

Performance - Latency Reduction

Data placement (HPF, STAPL, Chapel)

Use knowledge of algorithm access pattern to place all data for a computation near executing processor.

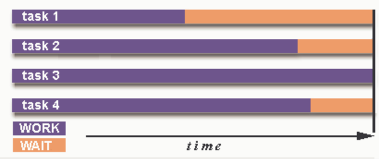
```
INTEGER, DIMENSION(1:16):: A,B
!HPF$ DISTRIBUTE(BLOCK) :: A
!HPF$ ALIGN WITH A :: B
```



Work placement (STAPL, Charm++)

Migrate computation to processor near data and return final result. Natural in RMI based communication models.

Load Balancing



Keep all CPUs doing equal work.
Relies on good *work scheduling*.

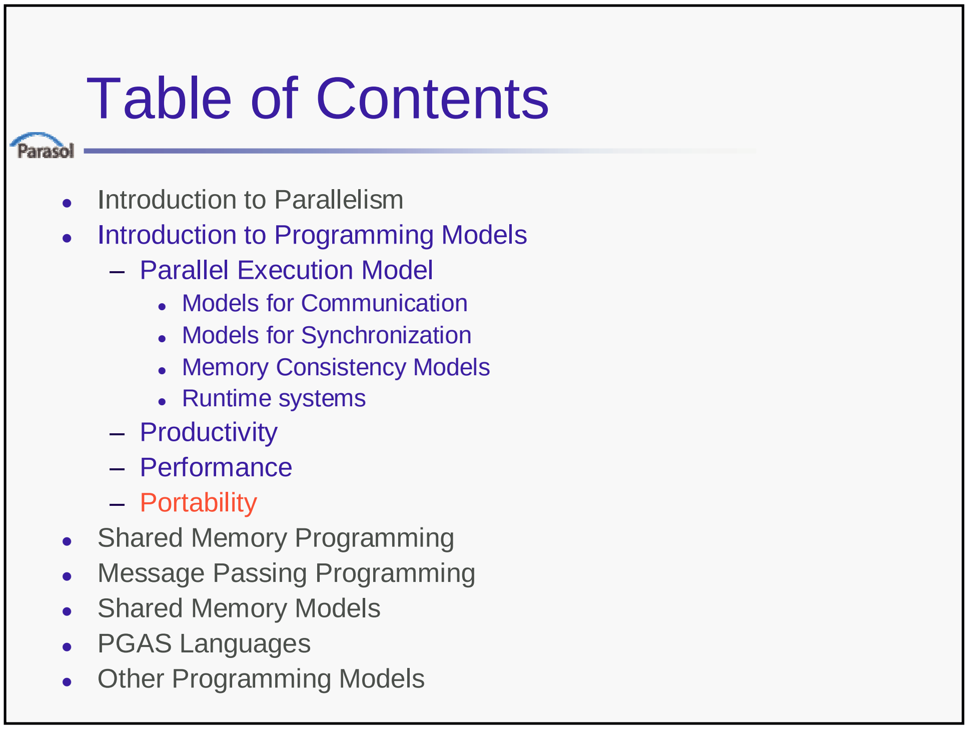
- Static **(MPI)**
  Decide before execution how to distribute work.
- Dynamic **(Cilk, TBB)**
  Adjust work distribution during execution.
  - Requires finer work granularity (> 1 task per CPU)
    Some models change granularity as needed (minimize overhead).
  - Work Stealing
    Allow idle processors to 'steal' queued work from busier processors.

Enabling a High Degree of Parallelism

Parallel models must strive for a high degree of parallelism for maximum performance.

Makes transparent latency hiding easy.

Enables finer granularity needed for load balancing.



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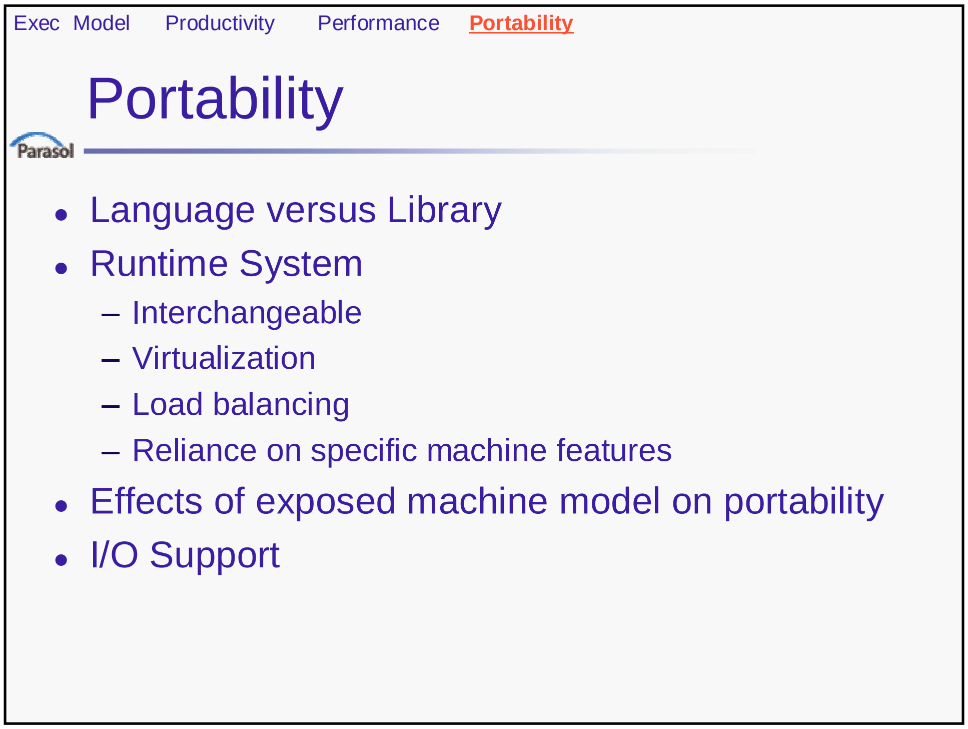


Exec Model Productivity Performance **Portability**

Portability

- Language versus Library
- Runtime System
  - Interchangeable
  - Virtualization
  - Load balancing
  - Reliance on specific machine features
- Effects of exposed machine model on portability
- I/O Support

Exec Model Productivity Performance **Portability**

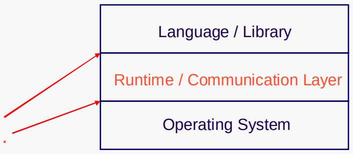
Language versus Library

- Models with specialized language require a compiler to be ported and sometimes additional runtime support.
  - Cray's **Chapel**, **Titanium**, Sun's **Fortress**.
- Library approaches leverage standard toolchains, and often rely on widely available standardized components.
  - **STAPL** requires C++, Boost, and a communication subsystem (MPI, OpenMP Pthreads).
  - **MPI** requires communication layer interfaceand command wrappers (mpirun) to use portable versions (MPICH or LamMPI). Incremental customization can improve performance.

Exec Model Productivity Performance **Portability**

Runtime System

- **Interchangeable**
  Runtime system (e.g., threading and communication management) specific to model or is it modular?
- **Processor Virtualization**
  How are logical processes mapped to processors?
  Is it a 1:1 mapping or multiple processes per processor?



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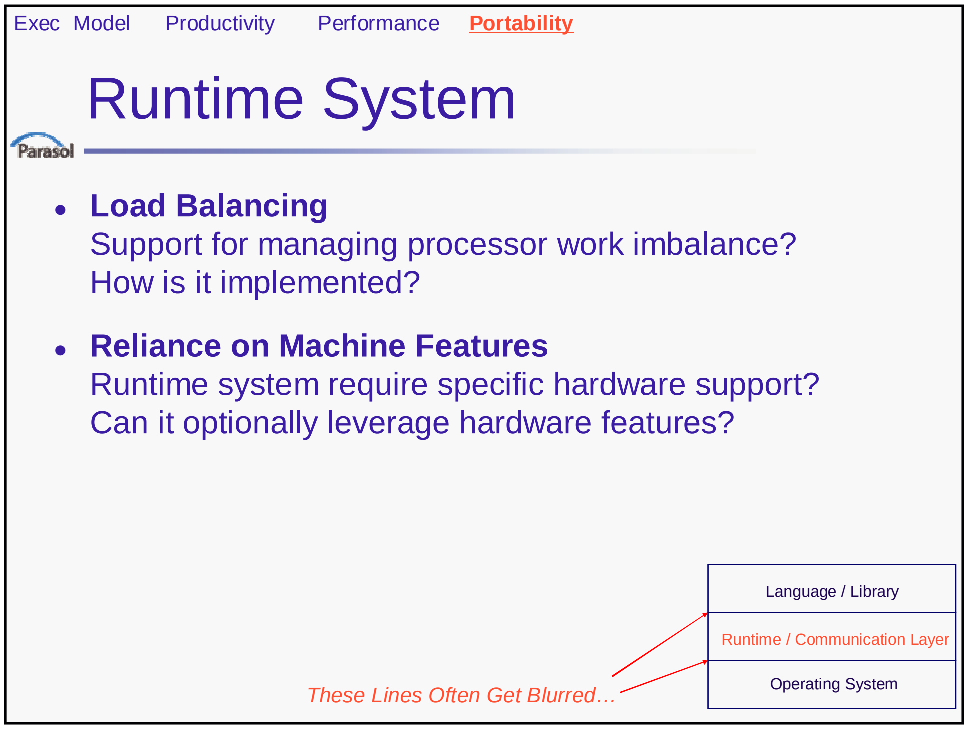


Runtime System

- **Load Balancing**
  Support for managing processor work imbalance?
  How is it implemented?

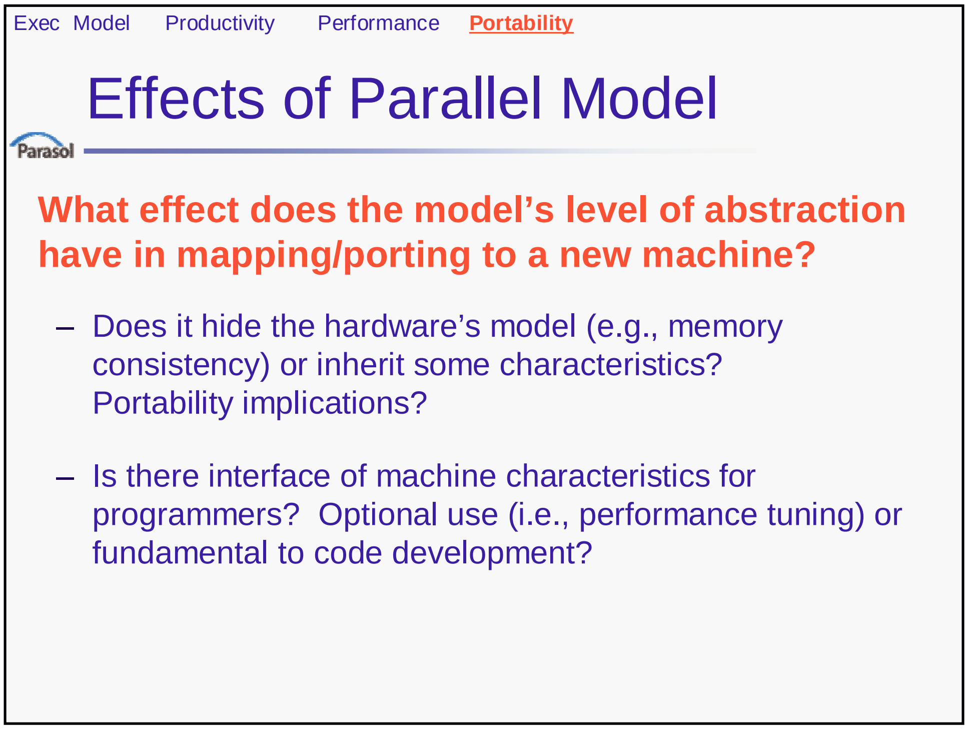
- **Reliance on Machine Features**
  Runtime system require specific hardware support?
  Can it optionally leverage hardware features?

Language / Library

Runtime / Communication Layer

Operating System

These Lines Often Get Blurred…



Effects of Parallel Model

What effect does the model's level of abstraction have in mapping/porting to a new machine?

- Does it hide the hardware's model (e.g., memory consistency) or inherit some characteristics? Portability implications?

- Is there interface of machine characteristics for programmers? Optional use (i.e., performance tuning) or fundamental to code development?

Support for I/O

Some parallel models specifically address I/O, providing mechanisms that provide an abstract view to various disk subsystems.

ROMIO - *portable I/O extension included with MPI (Message Passing Interface).*

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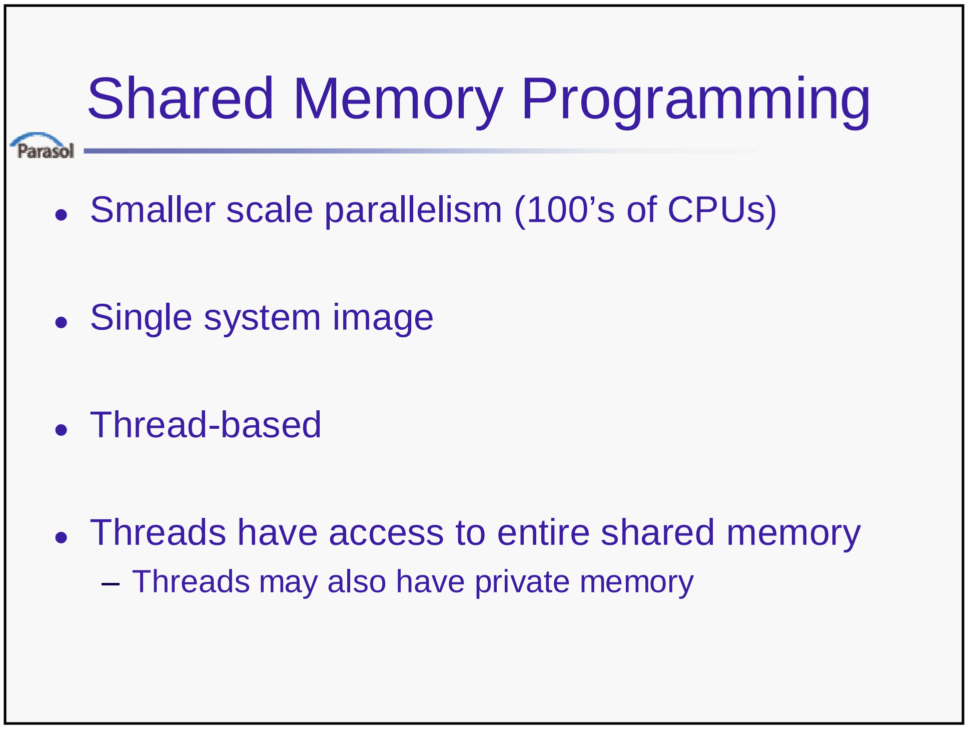
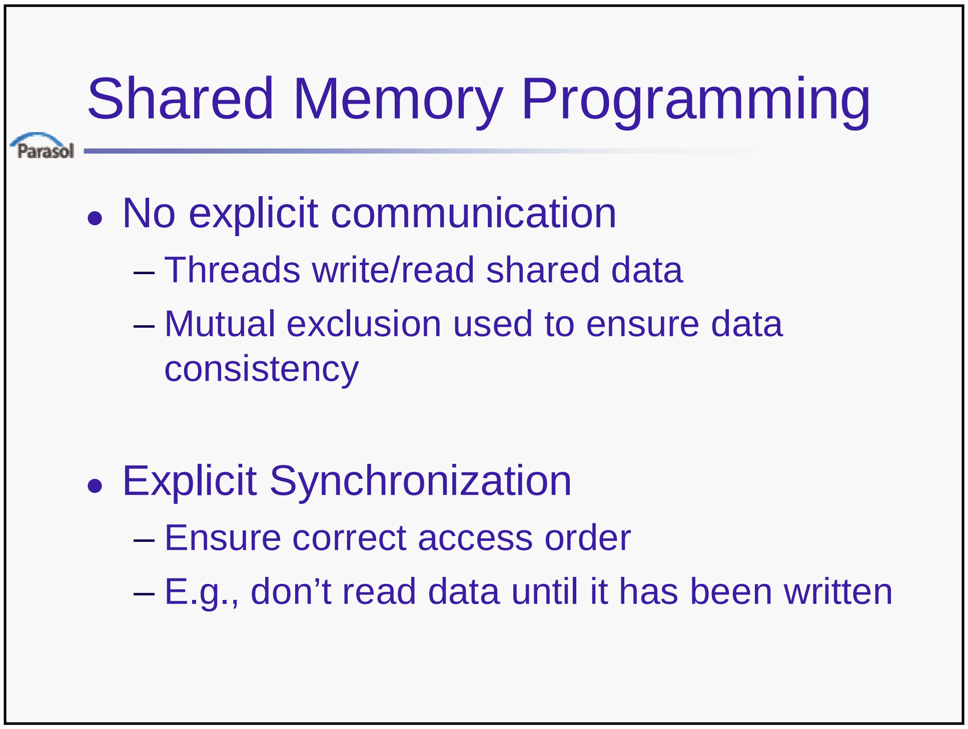


Shared Memory Programming

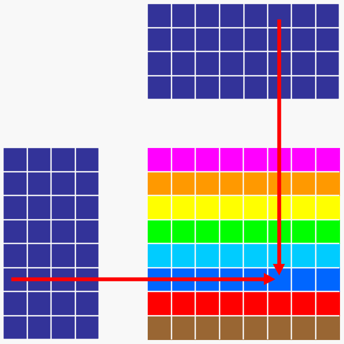
- Smaller scale parallelism (100’s of CPUs)
- Single system image
- Thread-based
- Threads have access to entire shared memory
  - Threads may also have private memory



Shared Memory Programming

- No explicit communication
  - Threads write/read shared data
  - Mutual exclusion used to ensure data consistency
- Explicit Synchronization
  - Ensure correct access order
  - E.g., don’t read data until it has been written

Example - Matrix Multiply



```
for(int i=0; i<M; ++i) {
  for(int j=0; j<N; ++j) {
    for(int k=0; k<L; ++k) {
      C[i][j] +=
          A[i][k]*B[k][j];
    }
  }
}
```

One way to parallelize is to compute each row Independently.

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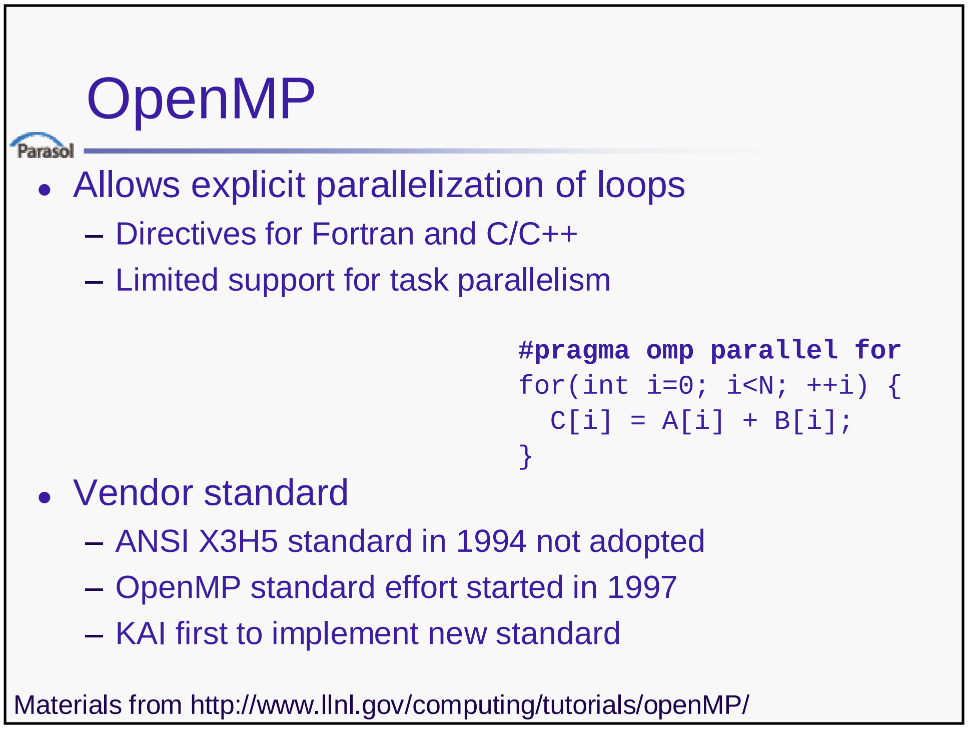


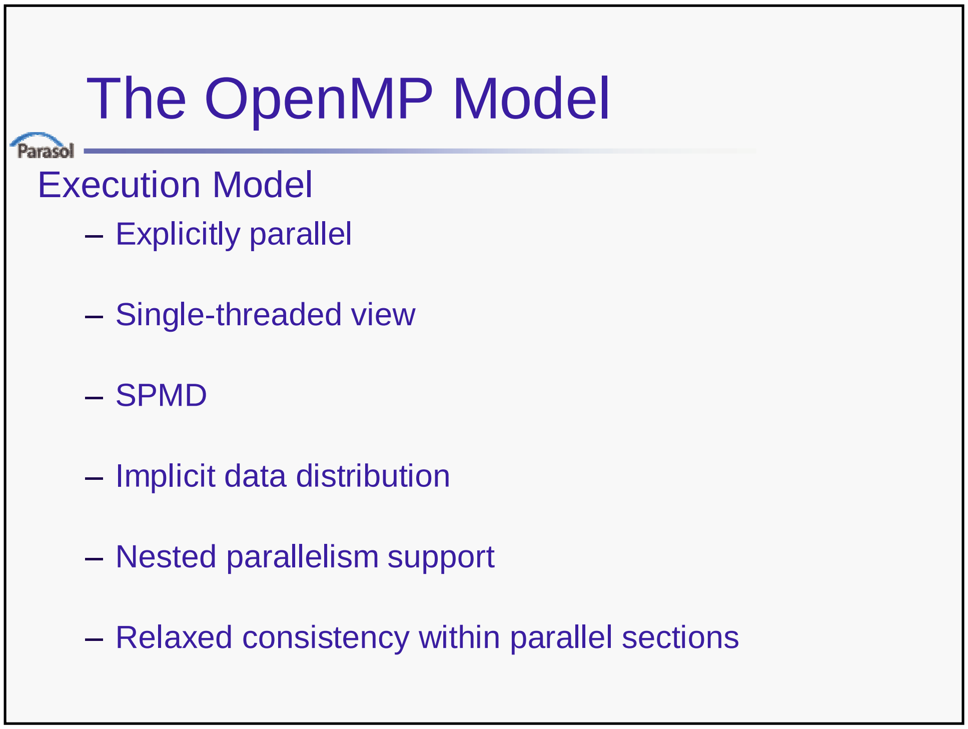
OpenMP

- Allows explicit parallelization of loops
  - Directives for Fortran and C/C++
  - Limited support for task parallelism

```
#pragma omp parallel for
for(int i=0; i<N; ++i) {
  C[i] = A[i] + B[i];
}
```

- Vendor standard
  - ANSI X3H5 standard in 1994 not adopted
  - OpenMP standard effort started in 1997
  - KAI first to implement new standard

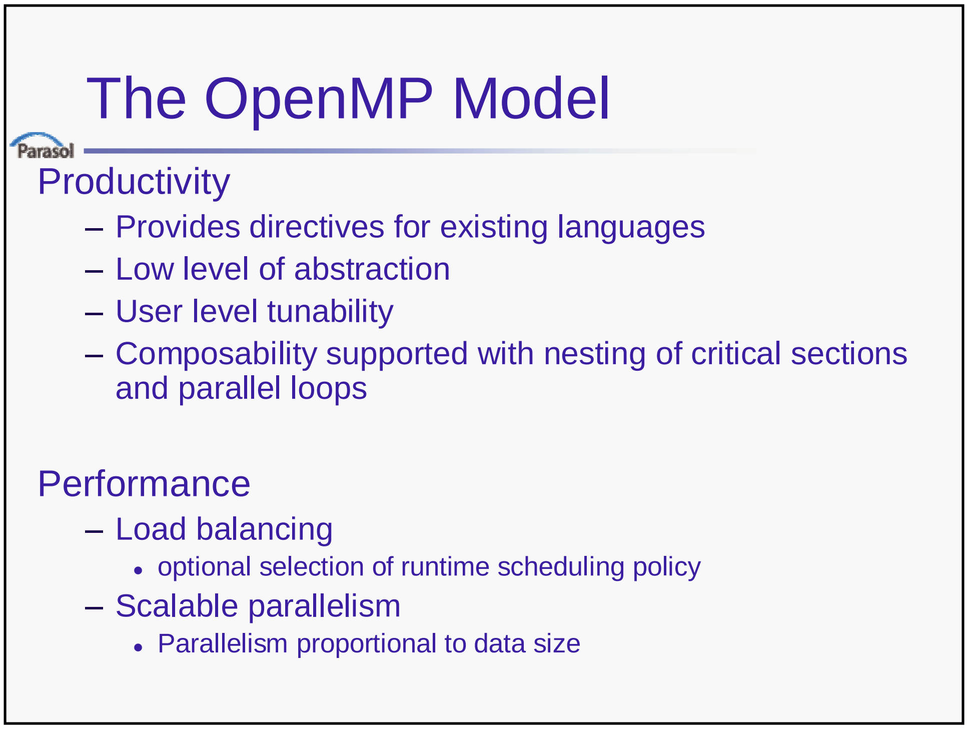
Materials from http://www.llnl.gov/computing/tutorials/openMP/



The OpenMP Model

Execution Model

- Explicitly parallel
- Single-threaded view
- SPMD
- Implicit data distribution
- Nested parallelism support
- Relaxed consistency within parallel sections



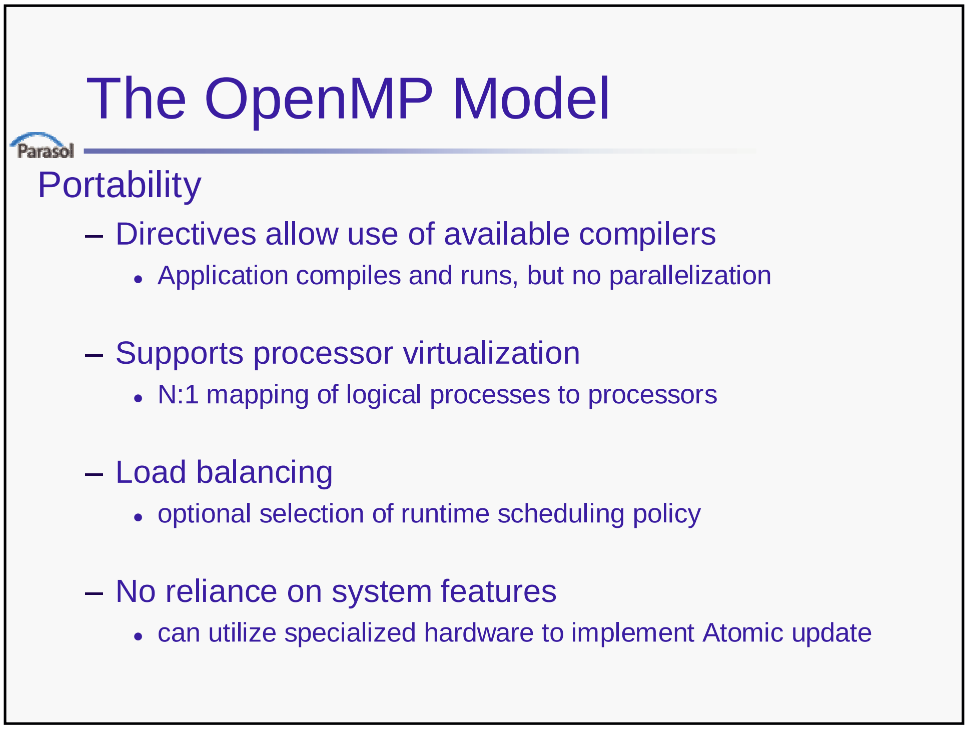
The OpenMP Model

Productivity

- – Provides directives for existing languages
- – Low level of abstraction
- – User level tunability
- – Composability supported with nesting of critical sections and parallel loops

Performance

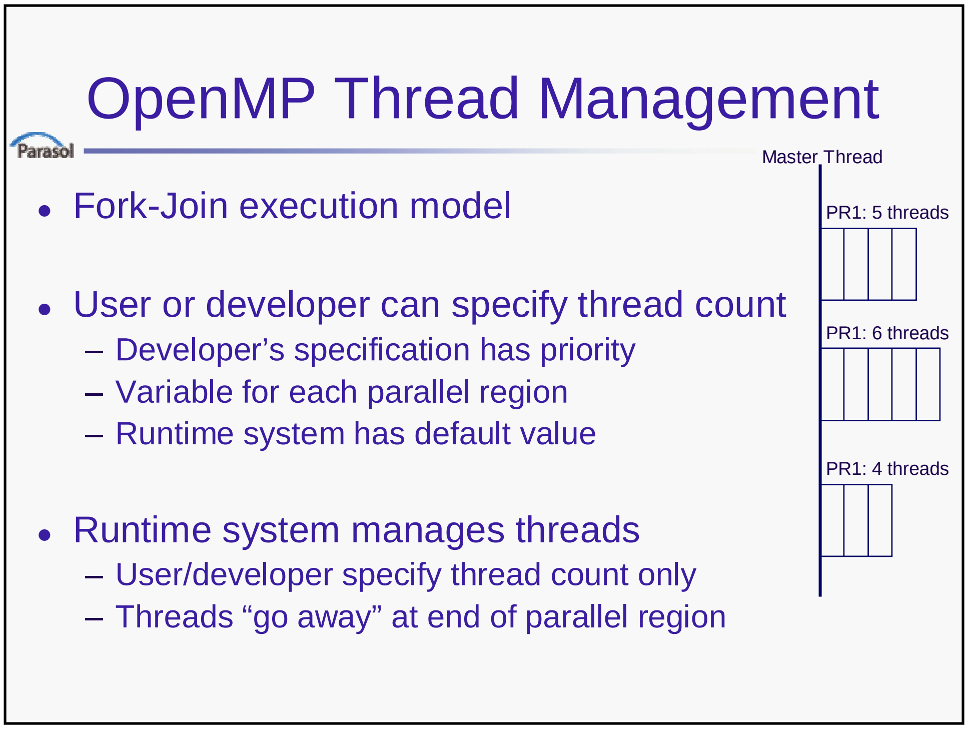
- – Load balancing
  - optional selection of runtime scheduling policy
- – Scalable parallelism
  - Parallelism proportional to data size



The OpenMP Model

Portability

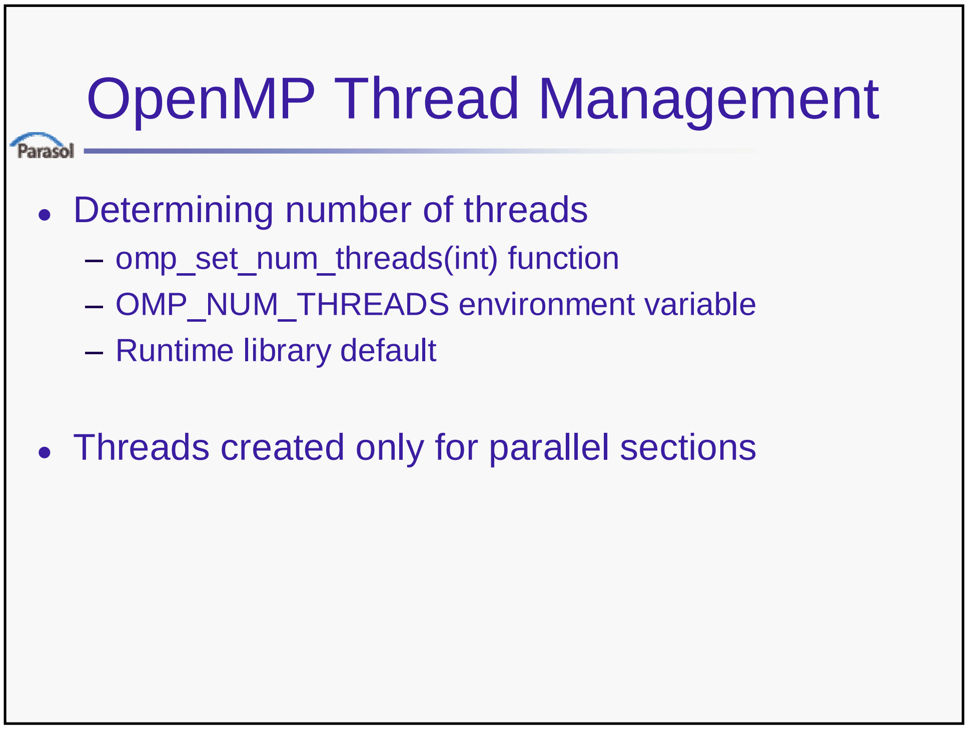
- – Directives allow use of available compilers
  - Application compiles and runs, but no parallelization
- – Supports processor virtualization
  - N:1 mapping of logical processes to processors
- – Load balancing
  - optional selection of runtime scheduling policy
- – No reliance on system features
  - can utilize specialized hardware to implement Atomic update



OpenMP Thread Management

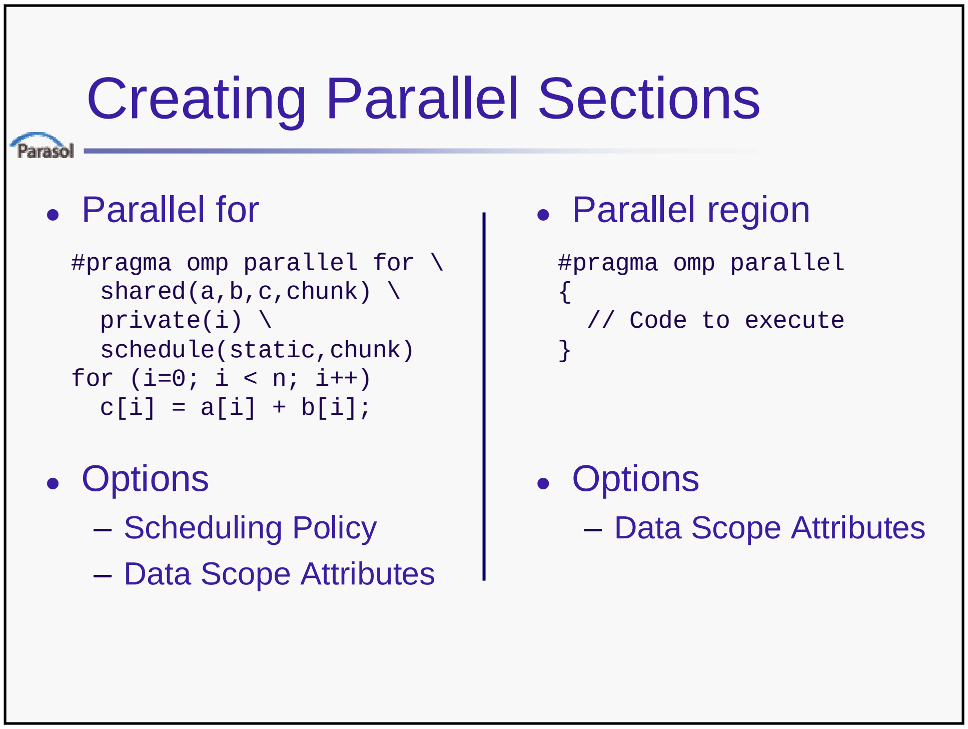
- Fork-Join execution model
- User or developer can specify thread count
  - Developer's specification has priority
  - Variable for each parallel region
  - Runtime system has default value
- Runtime system manages threads
  - User/developer specify thread count only
  - Threads "go away" at end of parallel region

Master Thread
PR1: 5 threads
PR1: 6 threads
PR1: 4 threads



OpenMP Thread Management

- Determining number of threads
  - omp_set_num_threads(int) function
  - OMP_NUM_THREADS environment variable
  - Runtime library default
- Threads created only for parallel sections



Creating Parallel Sections

- Parallel for

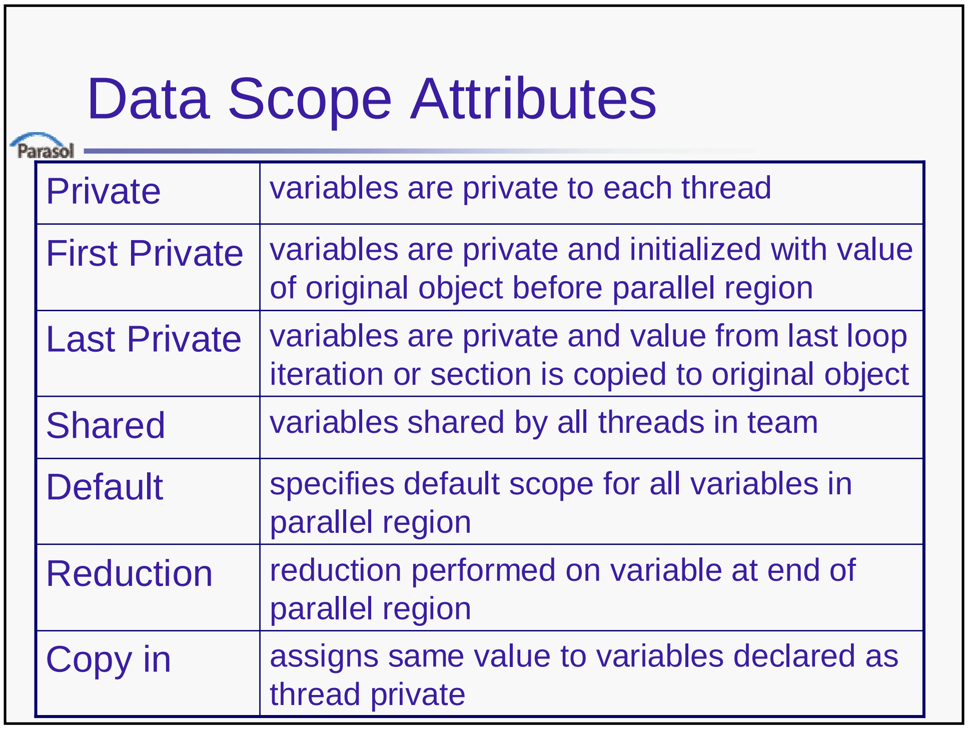
```
#pragma omp parallel for \
  shared(a,b,c,chunk) \
  private(i) \
  schedule(static,chunk)
for (i=0; i < n; i++)
  c[i] = a[i] + b[i];
```

- Options
  - Scheduling Policy
  - Data Scope Attributes

- Parallel region

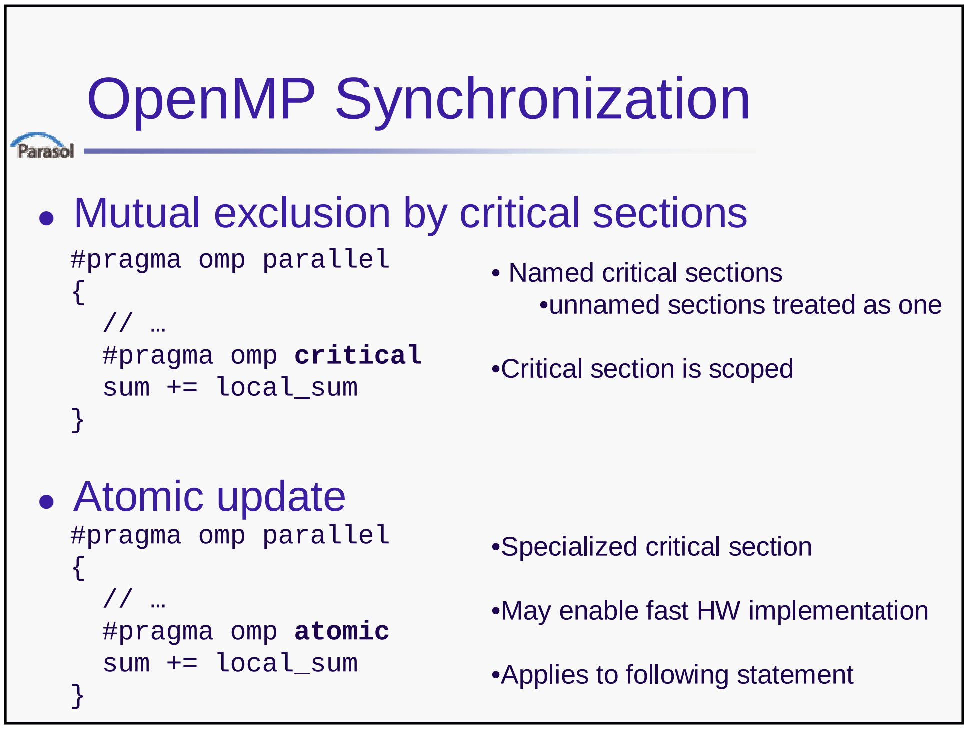
```
#pragma omp parallel
{
  // Code to execute
}
```

- Options
  - Data Scope Attributes



Data Scope Attributes

Private	variables are private to each thread
First Private	variables are private and initialized with value of original object before parallel region
Last Private	variables are private and value from last loop iteration or section is copied to original object
Shared	variables shared by all threads in team
Default	specifies default scope for all variables in parallel region
Reduction	reduction performed on variable at end of parallel region
Copy in	assigns same value to variables declared as thread private



OpenMP Synchronization

- Mutual exclusion by critical sections

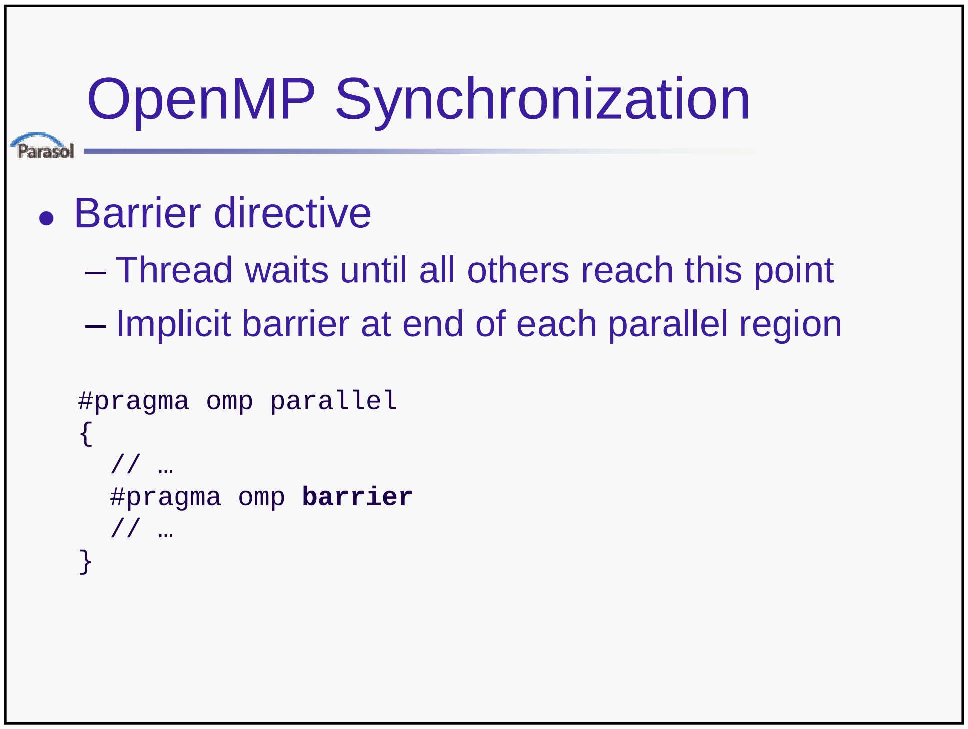
```
#pragma omp parallel
{
  // …
  #pragma omp critical
  sum += local_sum
}
```

- Named critical sections
    - unnamed sections treated as one
- Critical section is scoped

- Atomic update

```
#pragma omp parallel
{
  // …
  #pragma omp atomic
  sum += local_sum
}
```

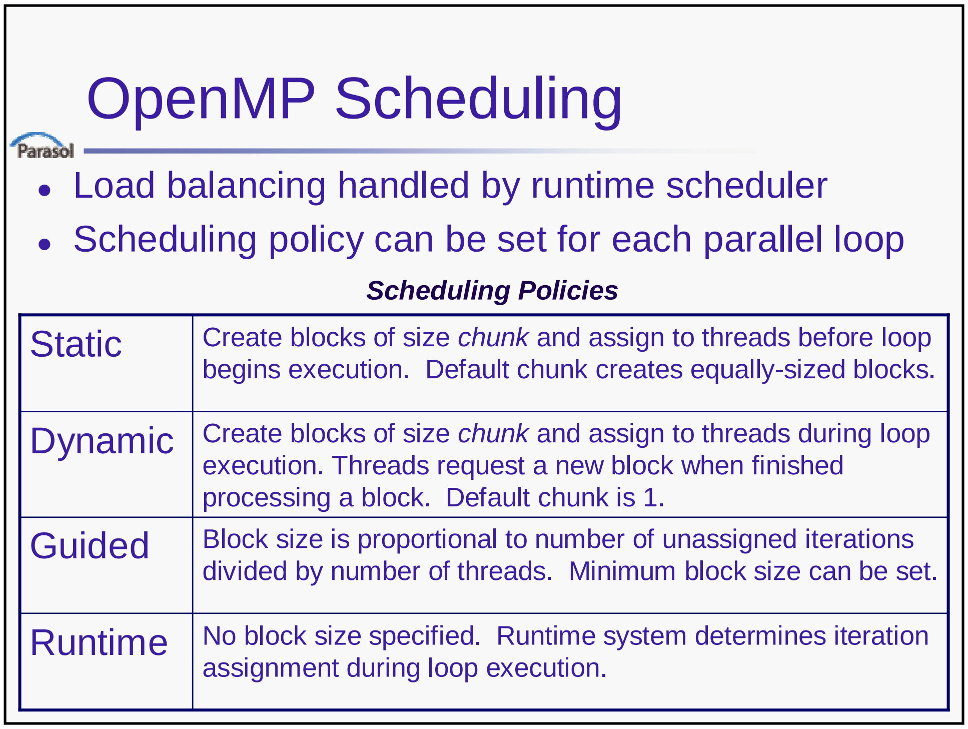
- Specialized critical section
- May enable fast HW implementation
- Applies to following statement



OpenMP Synchronization

- Barrier directive
    - – Thread waits until all others reach this point
    - – Implicit barrier at end of each parallel region

```
#pragma omp parallel
{
  // …
  #pragma omp barrier
  // …
}
```

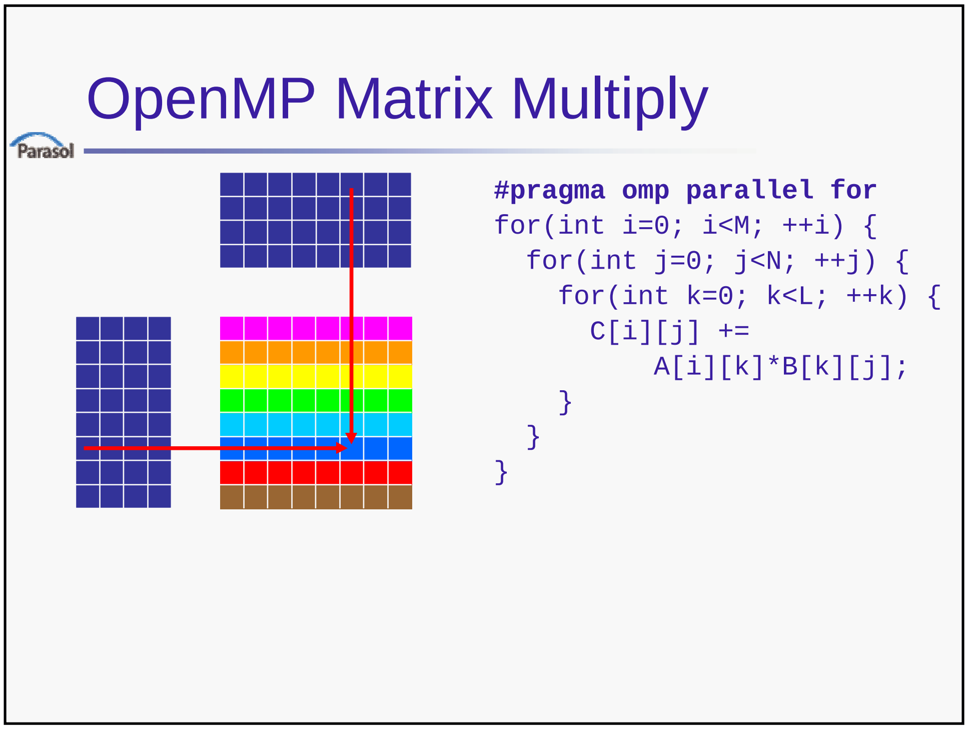


OpenMP Scheduling

- Load balancing handled by runtime scheduler
- Scheduling policy can be set for each parallel loop

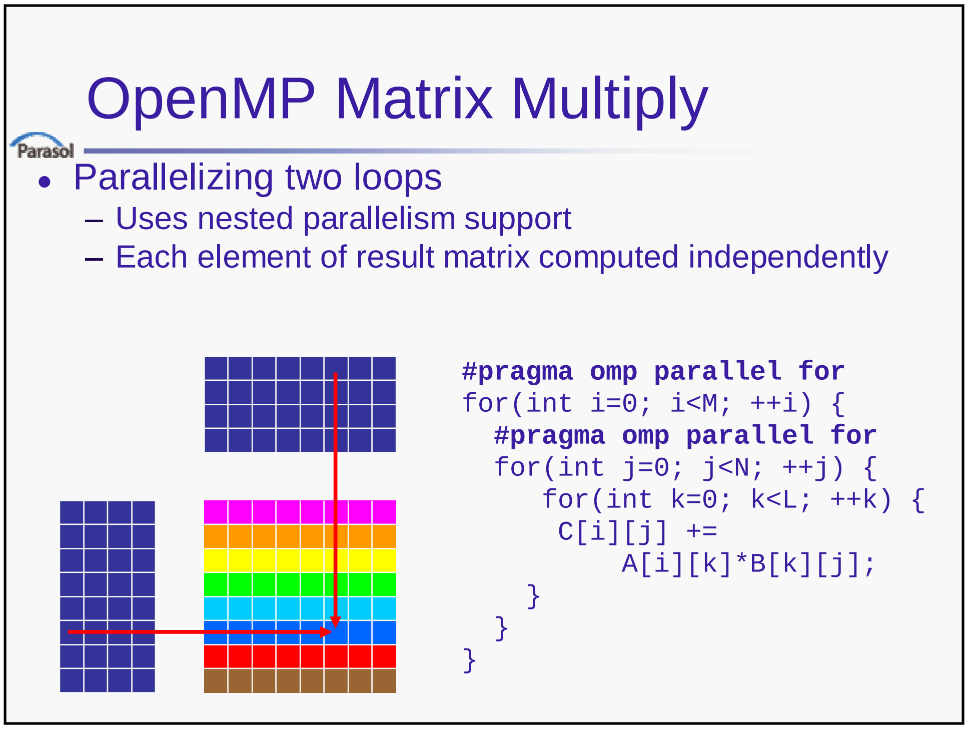
Scheduling Policies

Static	Create blocks of size *chunk* and assign to threads before loop begins execution. Default chunk creates equally-sized blocks.
Dynamic	Create blocks of size *chunk* and assign to threads during loop execution. Threads request a new block when finished processing a block. Default chunk is 1.
Guided	Block size is proportional to number of unassigned iterations divided by number of threads. Minimum block size can be set.
Runtime	No block size specified. Runtime system determines iteration assignment during loop execution.



OpenMP Matrix Multiply

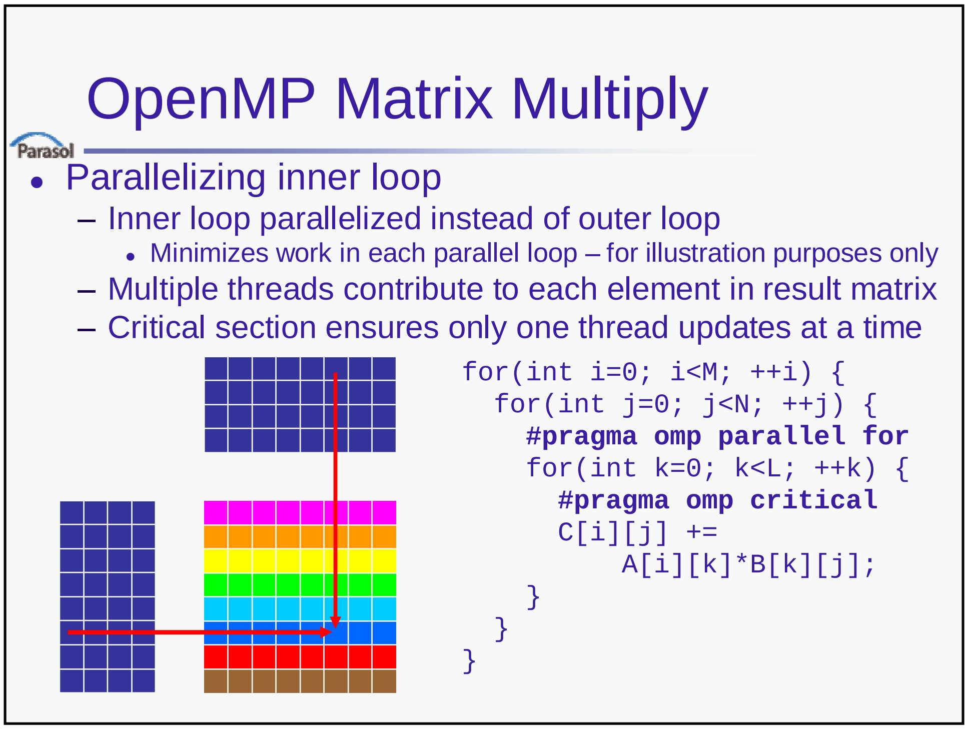
```
#pragma omp parallel for
for(int i=0; i<M; ++i) {
  for(int j=0; j<N; ++j) {
    for(int k=0; k<L; ++k) {
      C[i][j] +=
          A[i][k]*B[k][j];
    }
  }
}
```



OpenMP Matrix Multiply

- Parallelizing two loops
  - Uses nested parallelism support
  - Each element of result matrix computed independently

```
#pragma omp parallel for
for(int i=0; i<M; ++i) {
  #pragma omp parallel for
  for(int j=0; j<N; ++j) {
     for(int k=0; k<L; ++k) {
      C[i][j] +=
          A[i][k]*B[k][j];
    }
  }
}
```



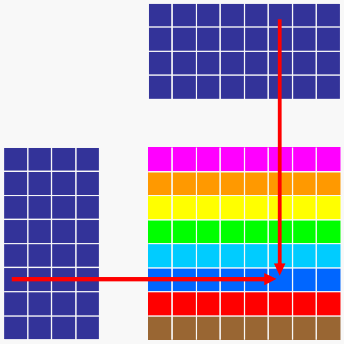
OpenMP Matrix Multiply

- Parallelizing inner loop
  - Inner loop parallelized instead of outer loop
    - Minimizes work in each parallel loop – for illustration purposes only
  - Multiple threads contribute to each element in result matrix
  - Critical section ensures only one thread updates at a time

```
for(int i=0; i<M; ++i) {
  for(int j=0; j<N; ++j) {
    #pragma omp parallel for
    for(int k=0; k<L; ++k) {
      #pragma omp critical
      C[i][j] +=
          A[i][k]*B[k][j];
    }
  }
}
```

OpenMP Matrix Multiply

- Use dynamic scheduling of iterations



```
#pragma omp parallel for \
schedule(dynamic)
for(int i=0; i<M; ++i) {
  for(int j=0; j<N; ++j) {
    for(int k=0; k<L; ++k) {
      C[i][j] +=
          A[i][k]*B[k][j];
    }
  }
}
```

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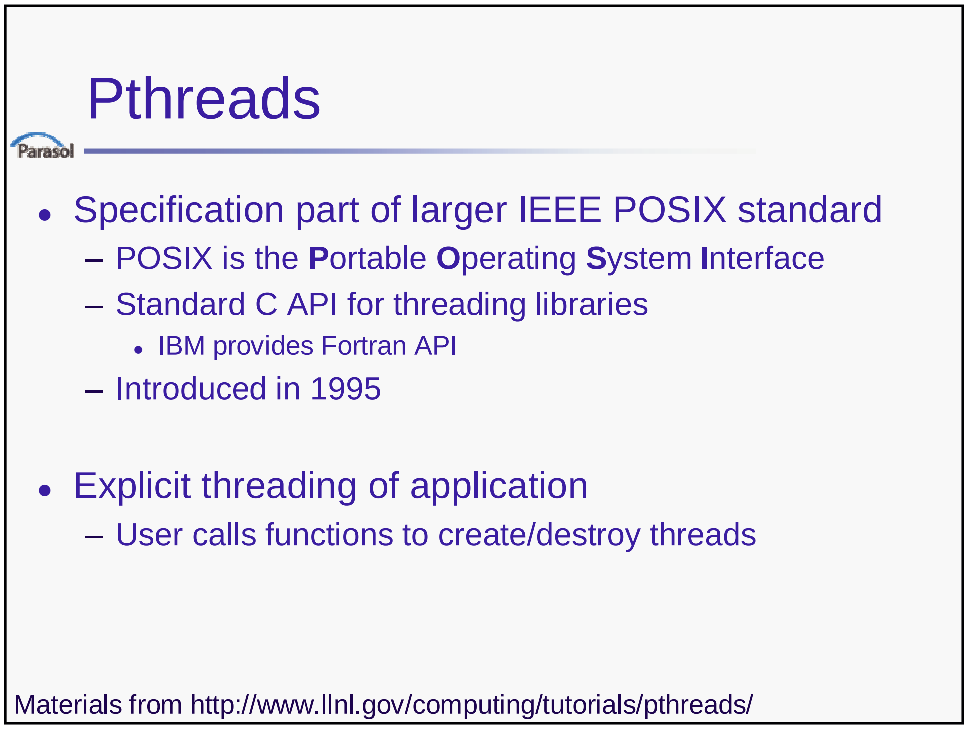
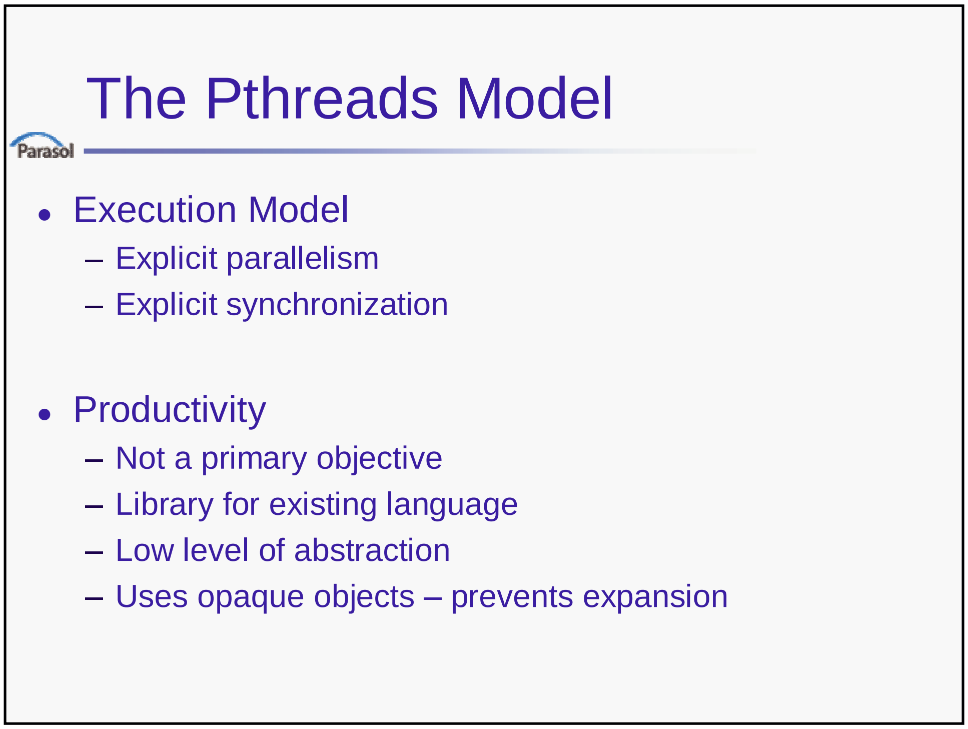


Pthreads

- Specification part of larger IEEE POSIX standard
  - POSIX is the **P**ortable **O**perating **S**ystem **I**nterface
  - Standard C API for threading libraries
    - IBM provides Fortran API
  - Introduced in 1995
- Explicit threading of application
  - User calls functions to create/destroy threads

Materials from http://www.llnl.gov/computing/tutorials/pthreads/



The Pthreads Model

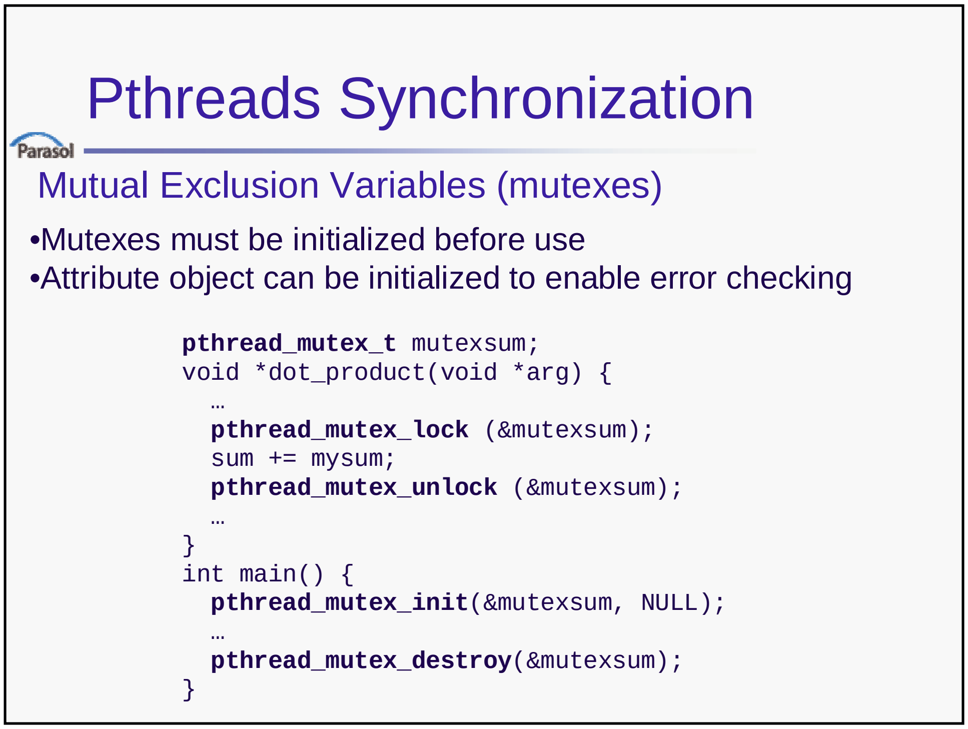
- Execution Model
  - Explicit parallelism
  - Explicit synchronization
- Productivity
  - Not a primary objective
  - Library for existing language
  - Low level of abstraction
  - Uses opaque objects – prevents expansion

The Pthreads Model

- Performance
  - No attempts to manage latency
  - Load balancing left to OS
  - Developer responsible for creating high degree of parallelism by spawning threads
- Portability
  - Library widely available

Pthreads Thread Management

- User creates/terminates threads
- Thread creation
  - `pthread_create`
  - Accepts a single argument (void *)
- Thread termination
  - `pthread_exit`
  - Called from within terminating thread



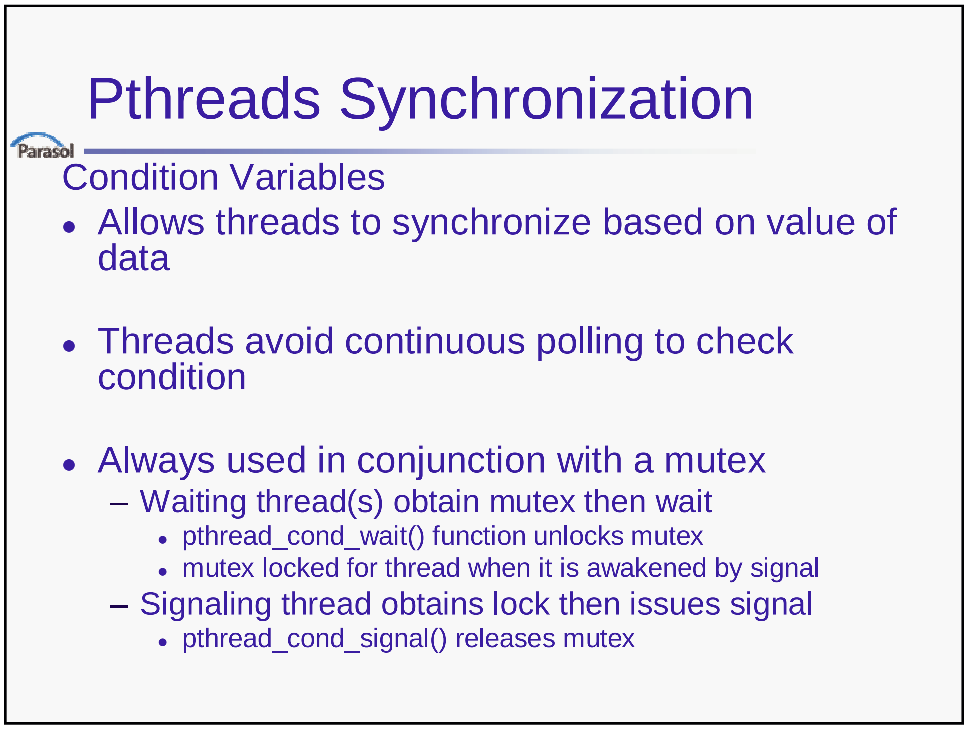
Pthreads Synchronization

Parasol

Mutual Exclusion Variables (mutexes)

•Mutexes must be initialized before use
•Attribute object can be initialized to enable error checking

```
pthread_mutex_t mutexsum;
void *dot_product(void *arg) {
  …
  pthread_mutex_lock (&mutexsum);
  sum += mysum;
  pthread_mutex_unlock (&mutexsum);
  …
}
int main() {
  pthread_mutex_init(&mutexsum, NULL);
  …
  pthread_mutex_destroy(&mutexsum);
}
```



Pthreads Synchronization

Parasol

Condition Variables

- Allows threads to synchronize based on value of data
- Threads avoid continuous polling to check condition
- Always used in conjunction with a mutex
  - Waiting thread(s) obtain mutex then wait
    - pthread_cond_wait() function unlocks mutex
    - mutex locked for thread when it is awakened by signal
  - Signaling thread obtains lock then issues signal
    - pthread_cond_signal() releases mutex

Condition Variable Example

Two threads update a counter
Third thread waits until counter reaches a threshold

```
pthread_mutex_t mtx;
pthread_cond_t cv;

int main() {
…
pthread_mutex_init(&mtx, NULL);
pthread_cond_init (&cv, NULL);
…
pthread_create(&threads[0], &attr,
               inc_count, (void *)&thread_ids[0]);
pthread_create(&threads[1], &attr,
               inc_count, (void *)&thread_ids[1]);
pthread_create(&threads[2], &attr,
               watch_count, (void *)&thread_ids[2]);
…
}
```

Condition Variable Example

Incrementing Threads

```
void *inc_count(void *idp) {
…
for (i=0; i<TCOUNT; ++i) {
  pthread_mutex_lock(&mtx);
  ++count;
  if (count == LIMIT)
    pthread_cond_signal(&cv);
  pthread_mutex_unlock(&mtx);
  …
}
…
}
```

Waiting Thread

```
void *watch_count(void *idp) {
…
pthread_mutex_lock(&mtx);
while (count < COUNT_LIMIT) {
  pthread_cond_wait(&cv, &mtx);
}
pthread_mutex_unlock(&mtx);
…
}
```

pthread_cond_broadcast() used if multiple threads waiting on signal

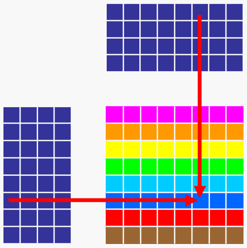
Pthreads Matrix Multiply

```
int tids[M];
pthread_t threads[M];
pthread_attr_t attr;
pthread_attr_init(&attr);
pthread_attr_setdetachstate(
  &attr,
  PTHREAD_CREATE_JOINABLE);

for (i=0; i<M; ++i) {
  tids[i] = i;
  pthread_create(&threads[i],
   &attr, work, (void *) &tids[i]);
}

for (i=0; i<M; ++i) {
  pthread_join(threads[i], NULL);
}
```

```
void* work(void* tid) {
  for(int j=0; j<N; ++j) {
    for(int k=0; k<L; ++k) {
      C[tid][j] +=
        A[tid][k]*B[k][j];
    }
  }
  pthread_exit(NULL);
}
```



References

OpenMP

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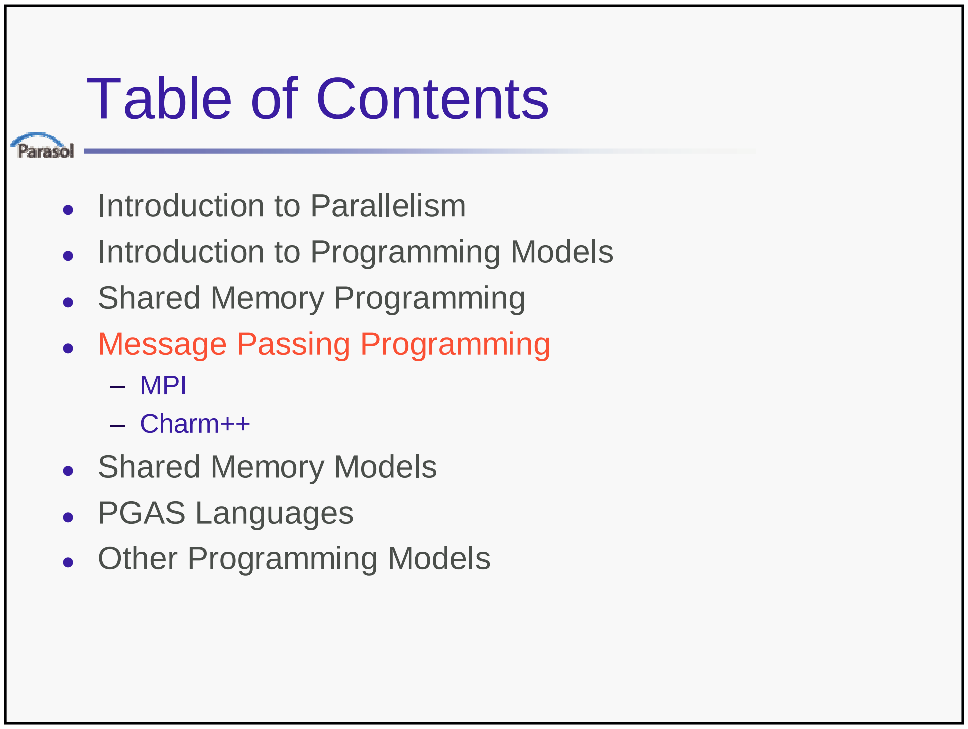
Pthreads

- http://www.llnl.gov/computing/tutorials/pthreads
- "Pthreads Programming". B. Nichols et al. O'Reilly and Associates.
- "Programming With POSIX Threads". D. Butenhof. Addison Wesley



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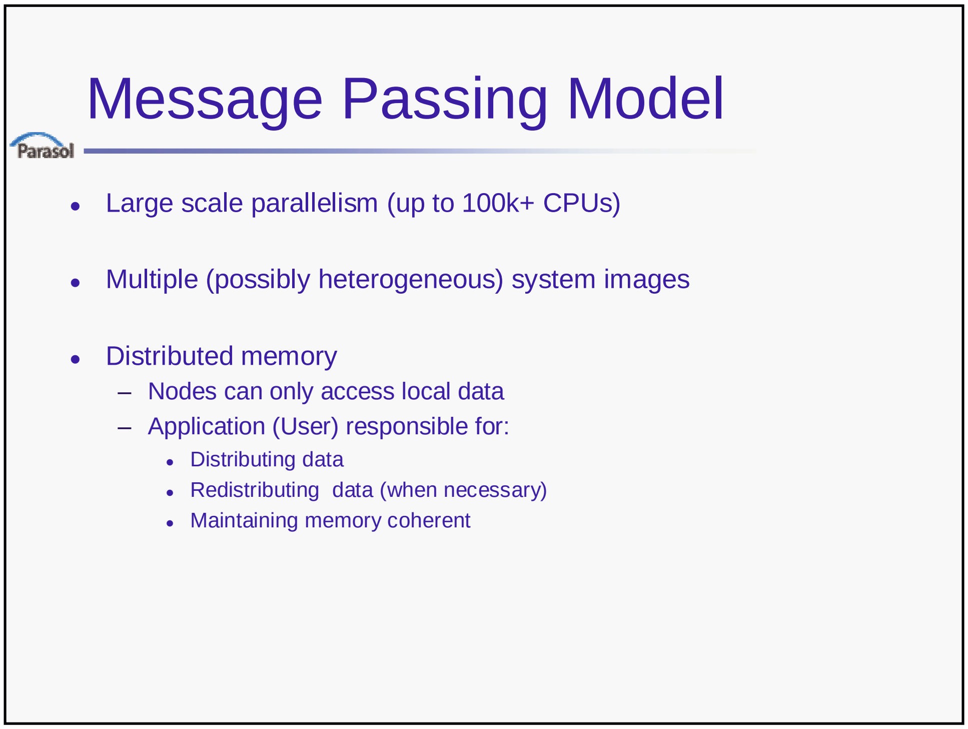
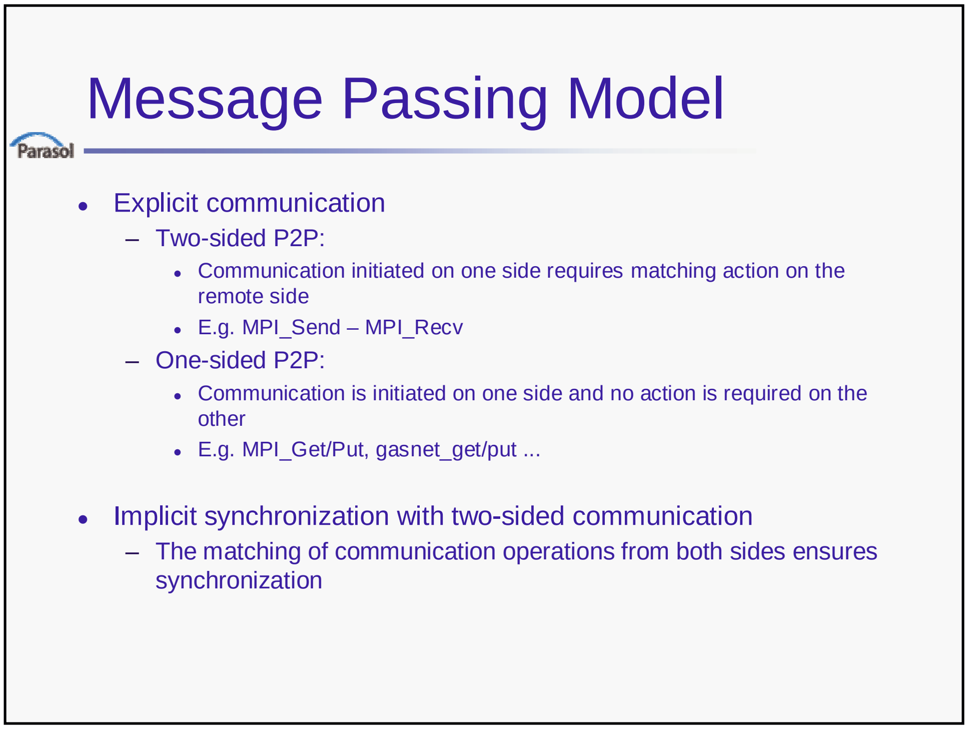


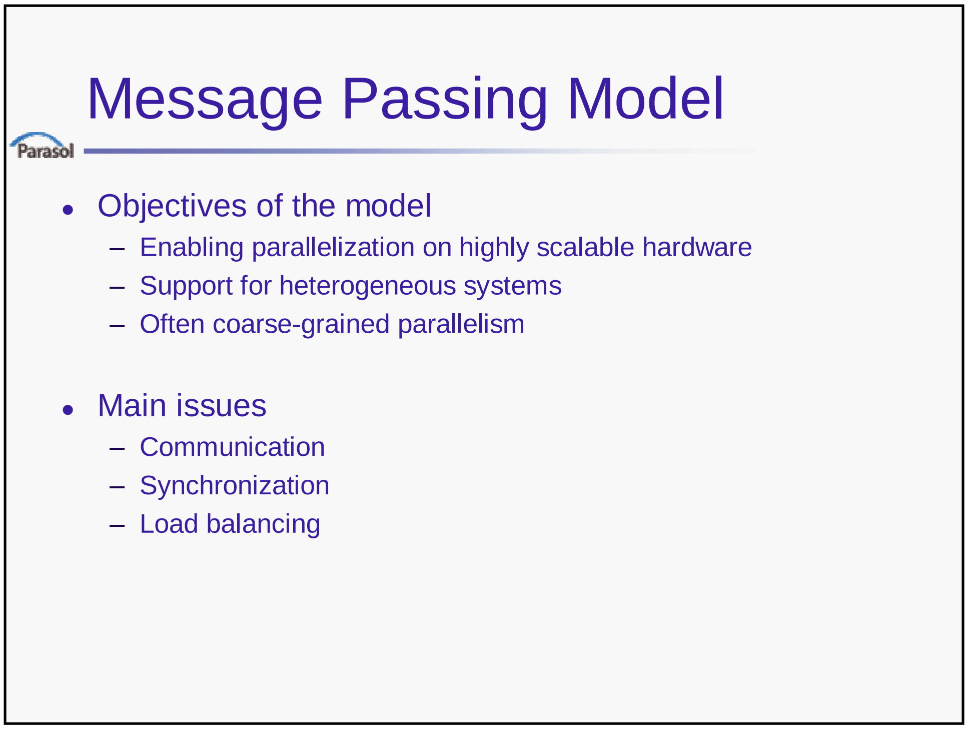
Message Passing Model

- Large scale parallelism (up to 100k+ CPUs)
- Multiple (possibly heterogeneous) system images
- Distributed memory
  - Nodes can only access local data
  - Application (User) responsible for:
    - Distributing data
    - Redistributing data (when necessary)
    - Maintaining memory coherent



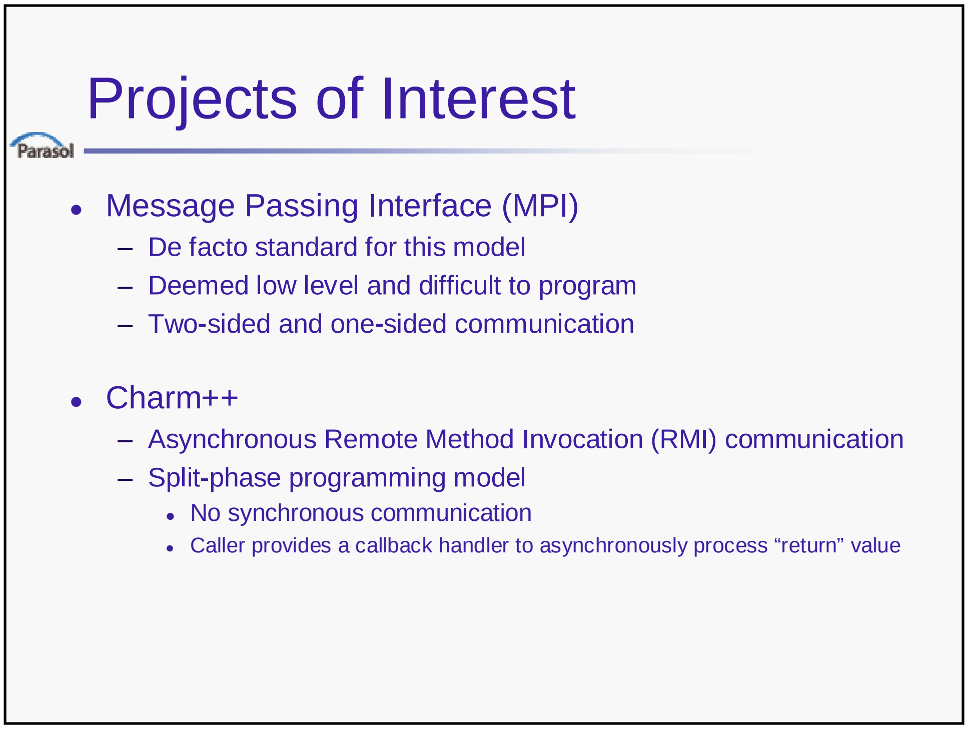
Message Passing Model

- Explicit communication
  - Two-sided P2P:
    - Communication initiated on one side requires matching action on the remote side
    - E.g. MPI_Send – MPI_Recv
  - One-sided P2P:
    - Communication is initiated on one side and no action is required on the other
    - E.g. MPI_Get/Put, gasnet_get/put ...
- Implicit synchronization with two-sided communication
  - The matching of communication operations from both sides ensures synchronization



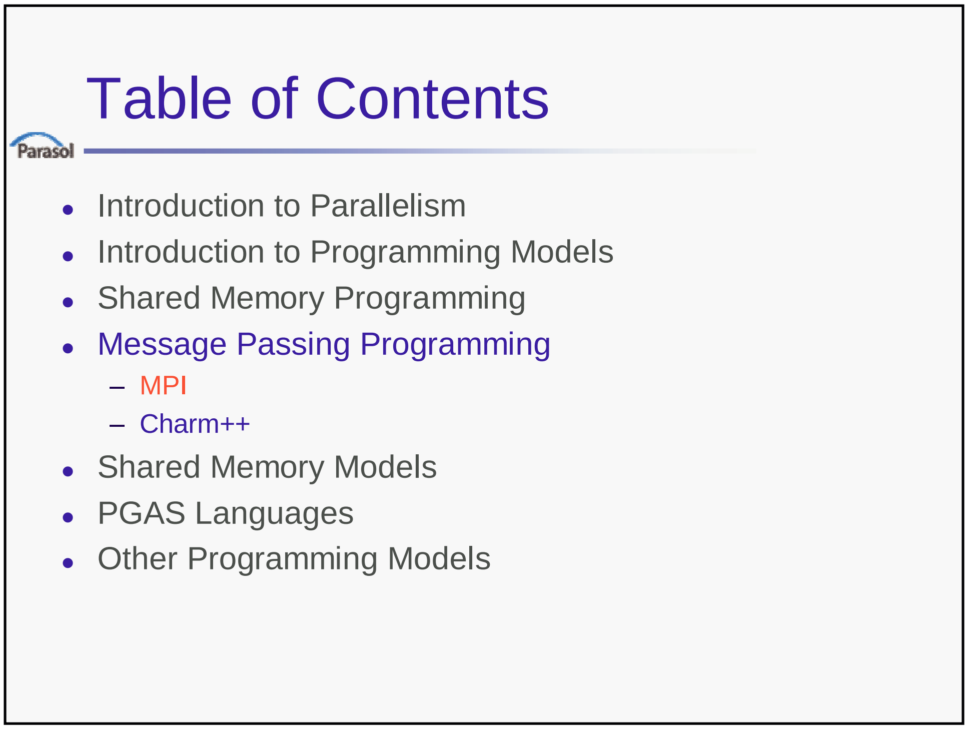
Message Passing Model

- Objectives of the model
  - Enabling parallelization on highly scalable hardware
  - Support for heterogeneous systems
  - Often coarse-grained parallelism
- Main issues
  - Communication
  - Synchronization
  - Load balancing



Projects of Interest

- Message Passing Interface (MPI)
  - De facto standard for this model
  - Deemed low level and difficult to program
  - Two-sided and one-sided communication
- Charm++
  - Asynchronous Remote Method Invocation (RMI) communication
  - Split-phase programming model
    - No synchronous communication
    - Caller provides a callback handler to asynchronously process “return” value



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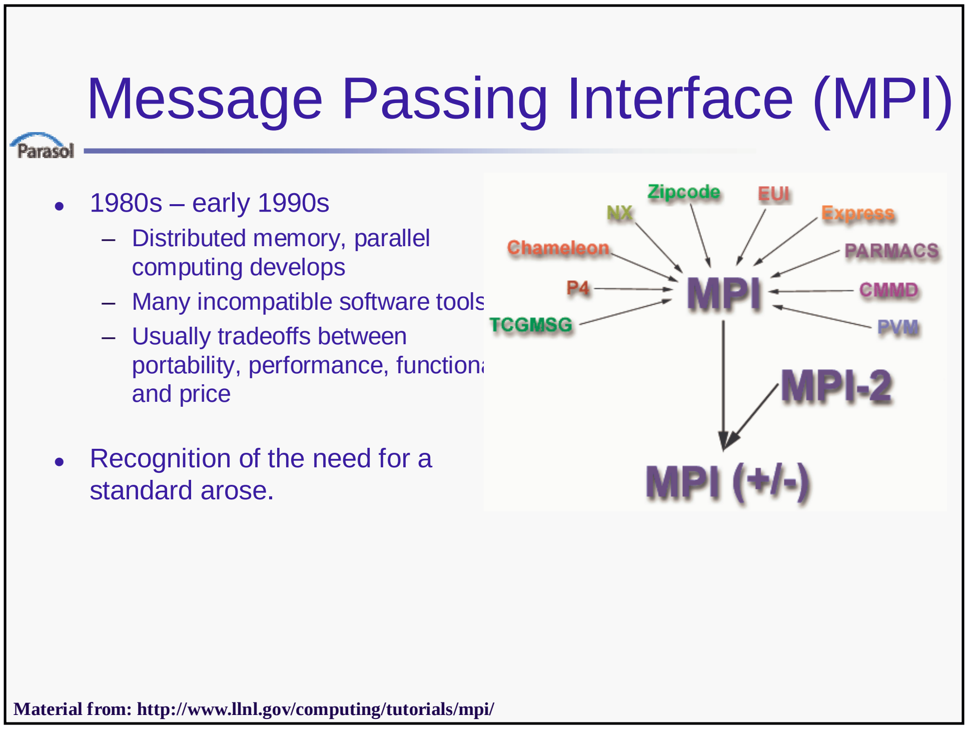
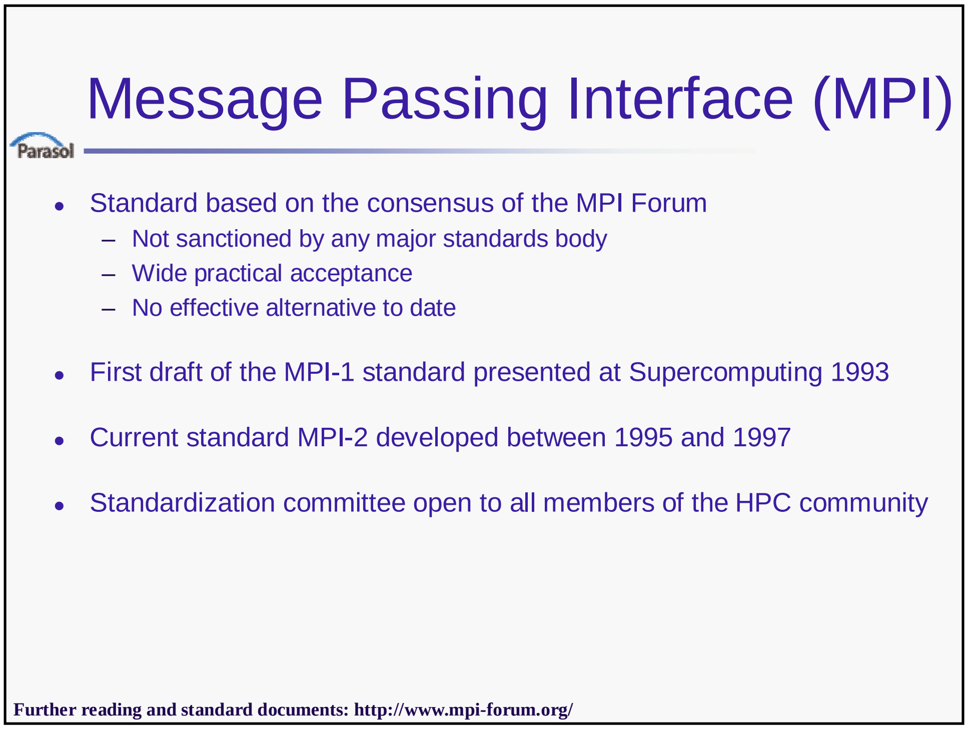


Message Passing Interface (MPI)

- 1980s – early 1990s
  - Distributed memory, parallel computing develops
  - Many incompatible software tools
  - Usually tradeoffs between portability, performance, functiona and price
- Recognition of the need for a standard arose.

Material from: http://www.llnl.gov/computing/tutorials/mpi/



Message Passing Interface (MPI)

- Standard based on the consensus of the MPI Forum
  - Not sanctioned by any major standards body
  - Wide practical acceptance
  - No effective alternative to date
- First draft of the MPI-1 standard presented at Supercomputing 1993
- Current standard MPI-2 developed between 1995 and 1997
- Standardization committee open to all members of the HPC community

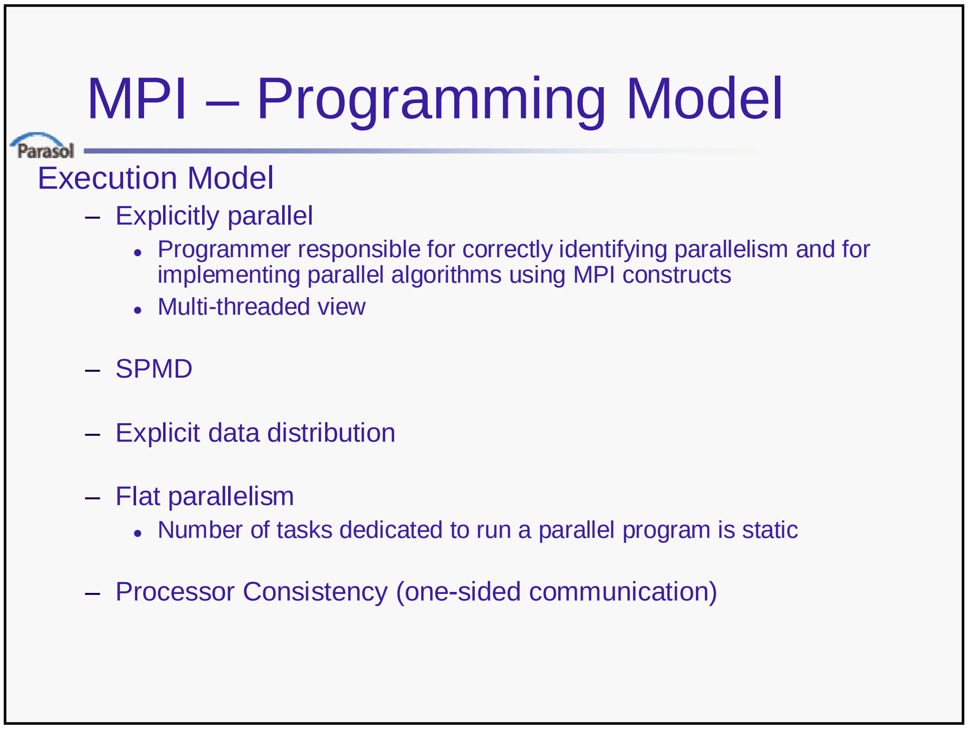
Further reading and standard documents: http://www.mpi-forum.org/

Message Passing Interface (MPI)

- Objectives
  - High performance and scalability
  - Portability
  - Productivity is not an objective (actually it was)
- Used as communication layer for higher-level libraries
  - Often for more productivity-oriented libraries
  - ISO/OSI layer-5 interface
    - Communication is reliable and sessions are managed internally
    - Data is not structured

MPI: Specification, not Implementation

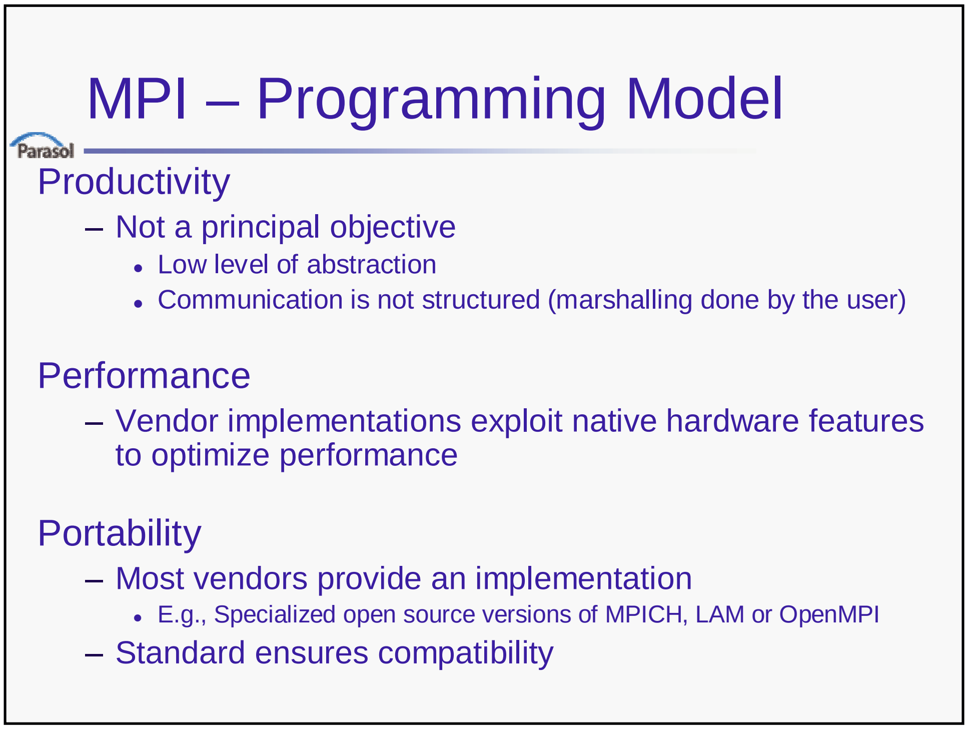
- Language Independent Specification (LIS)
- Library implementations of MPI vary in:
  - Performance
    - Target or rely on specific hardware (RDMA, PIM, Coprocessors …)
    - Provide load-balancing and processor virtualization (e.g., AMPI)
  - Functionality
    - Support for parallel I/O
    - Support for multithreading within MPI processes
- Standard provides language bindings for Fortran, C and C++
- Implementations usually provide APIs for C, C++ and Fortran
- Project implementations for Python, OCaml, and Java



MPI – Programming Model

Execution Model

- Explicitly parallel
  - Programmer responsible for correctly identifying parallelism and for implementing parallel algorithms using MPI constructs
  - Multi-threaded view
- SPMD
- Explicit data distribution
- Flat parallelism
  - Number of tasks dedicated to run a parallel program is static
- Processor Consistency (one-sided communication)



MPI – Programming Model

Productivity

- Not a principal objective
  - Low level of abstraction
  - Communication is not structured (marshalling done by the user)

Performance

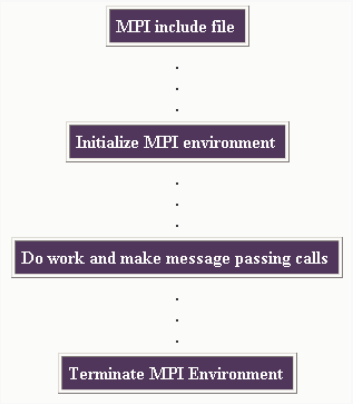
- Vendor implementations exploit native hardware features to optimize performance

Portability

- Most vendors provide an implementation
  - E.g., Specialized open source versions of MPICH, LAM or OpenMPI
- Standard ensures compatibility

MPI – Program Structure

General program structure



MPI include file

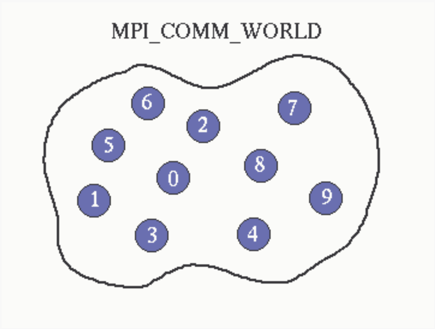
Initialize MPI environment

Do work and make message passing calls

Terminate MPI Environment

Communicators and groups

- Collection of processes that may communicate
- Unique rank (processor ID) within communicator
- Default communicator: MPI_COMM_WORLD



Materials from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

Types of Point-to-Point Operations:

- Message passing between two, and only two, different MPI tasks
  - One task performs a send operation
  - The other task matches with a receive operation
- Different types of send/receive routines used for different purposes
  - Synchronous send
  - Blocking send / blocking receive
  - Non-blocking send / non-blocking receive
  - Buffered send
  - Combined send/receive
  - "Ready" send
- Any type of send can be paired with any type of receive
- Test and Probe routines to check the status of pending operations

Material from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

Blocking vs. Non-blocking

- Most routines can be used in either blocking or non-blocking mode
- Blocking communication routines
  - Blocking send routines only return when it is safe to reuse send buffer
    - Modifications to send buffer will not affect data received on the remote side
      - Data already sent
      - Data buffered in a system buffer
  - Blocking send calls can be synchronous
    - Handshaking with the receiver
  - Blocking send calls can be asynchronous
    - System buffer used to hold the data for eventual delivery to the receiver
  - Blocking receive calls only return after the data has arrived and is ready for use by the program

Materials from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

Blocking communication example

```
#include "mpi.h"
#include <stdio.h>

int main(int argc,char *argv[]) {
  int numtasks, rank, dest, source, rc, count, tag=1;
  char inmsg, outmsg='x';
  MPI_Status Stat;

  MPI_Init(&argc,&argv);
  MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);

  if (rank == 0) {
    dest = 1;
    source = 1;
    rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
    rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
  }
  else if (rank == 1) {
    dest = 0;
    source = 0;
    rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
    rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
  }

  rc = MPI_Get_count(&Stat, MPI_CHAR, &count);
  printf("Task %d: Received %d char(s) from task %d with tag %d \n",
         rank, count, Stat.MPI_SOURCE, Stat.MPI_TAG);

  MPI_Finalize();
}
```

Materials from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

Blocking vs. Non-blocking

- Non-blocking communication routines
  - Send and receive routines behave similarly
    - Return almost immediately
    - Do not wait for any communication events to complete
      - Message copying from user memory to system buffer space
      - Actual arrival of message
  - Operations "request" the MPI library to perform an operation
    - Operation is performed when its requirements are met (e.g., message arrives)
    - User cannot predict when that will happen
  - Unsafe to modify the application buffer until completion of operation
    - Wait and Test routines used to determine completion
- Non-blocking communications primarily used to overlap computation with communication and exploit possible performance gains

Material from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

Non-blocking communication example

```
MPI_Request reqs[4];
MPI_Status stats[4];

prev = rank-1;
next = rank+1;
if (rank == 0) prev = numtasks - 1;
if (rank == (numtasks - 1)) next = 0;

MPI_Irecv(&buf[0], 1, MPI_INT, prev, tag1, MPI_COMM_WORLD, &reqs[0]);
MPI_Irecv(&buf[1], 1, MPI_INT, next, tag2, MPI_COMM_WORLD, &reqs[1]);

MPI_Isend(&rank, 1, MPI_INT, prev, tag2, MPI_COMM_WORLD, &reqs[2]);
MPI_Isend(&rank, 1, MPI_INT, next, tag1, MPI_COMM_WORLD, &reqs[3]);

  {
    // do some work
    // work will overlap with previous communication
  }

MPI_Waitall(4, reqs, stats);
```

Materials from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

Order and Fairness

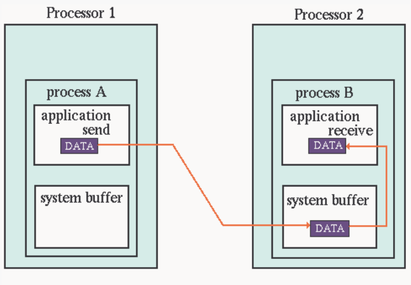
- Message Ordering
  - Messages do not overtake each other
    - If a sender sends two messages (Message 1 and Message 2) in succession to the same destination, and both match the same receive, the receive operation will receive Message 1 before Message 2.
    - If a receiver posts two receives (Receive 1 and Receive 2), in succession, and both match the same message, Receive 1 will receive the message before Receive 2.
  - Ordering is not thread-safe
    - If multiple threads participate in the communication, no order is guaranteed
- Fairness of Message Delivery
  - No fairness guarantee
    - Programmer responsible for preventing operation starvation
  - Example: task 0 sends a message to task 2. However, task 1 sends a competing message that matches task 2's receive. Only one of the sends will complete.

Material from: http://www.llnl.gov/computing/tutorials/mpi/

MPI – Point to Point Communication

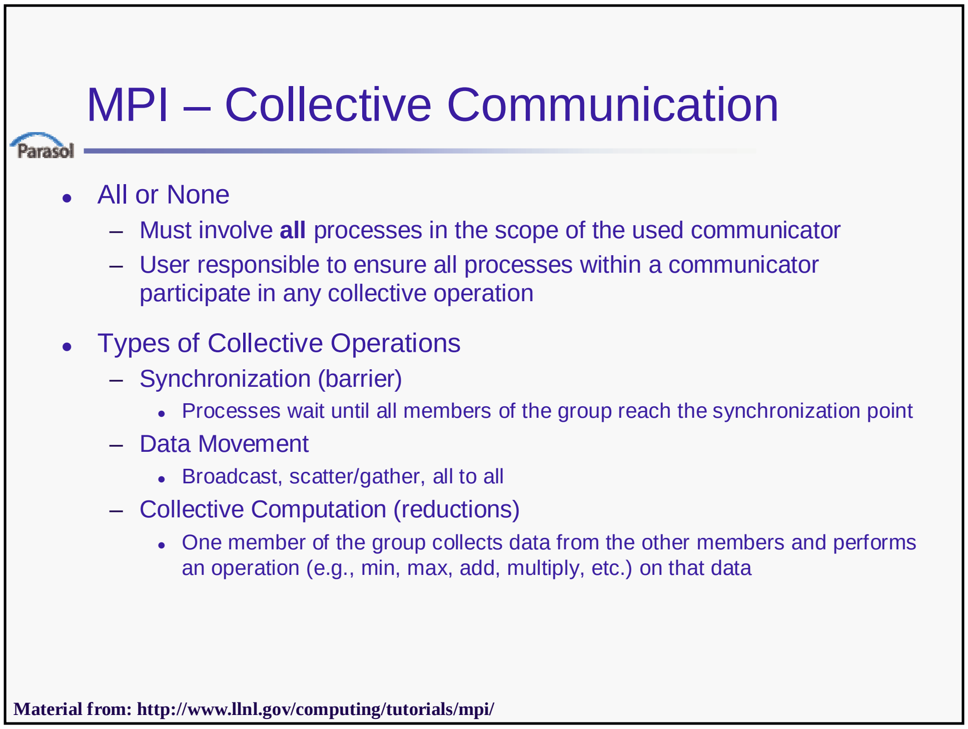
Buffering when tasks are out of sync

- If a receive operation is not ready, sent data is buffered
  - On receiving side, sending side or both
- User can manage buffering memory on sending side



Path of a message buffered at the receiving process

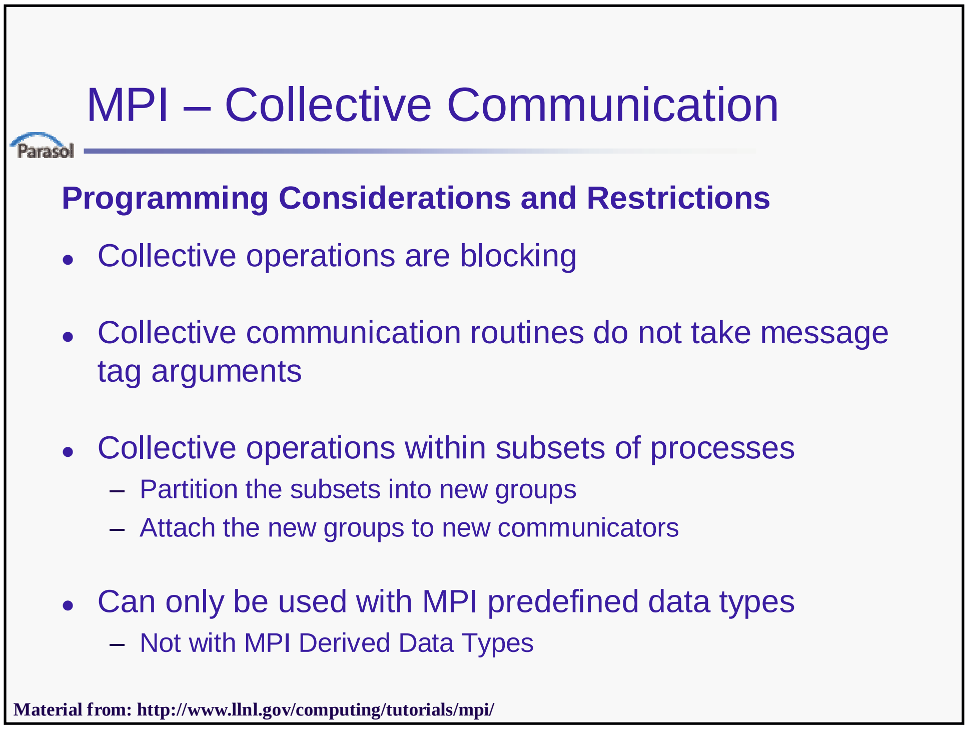
Material from: http://www.llnl.gov/computing/tutorials/mpi/



MPI – Collective Communication

- All or None
  - Must involve **all** processes in the scope of the used communicator
  - User responsible to ensure all processes within a communicator participate in any collective operation
- Types of Collective Operations
  - Synchronization (barrier)
    - Processes wait until all members of the group reach the synchronization point
  - Data Movement
    - Broadcast, scatter/gather, all to all
  - Collective Computation (reductions)
    - One member of the group collects data from the other members and performs an operation (e.g., min, max, add, multiply, etc.) on that data

Material from: http://www.llnl.gov/computing/tutorials/mpi/

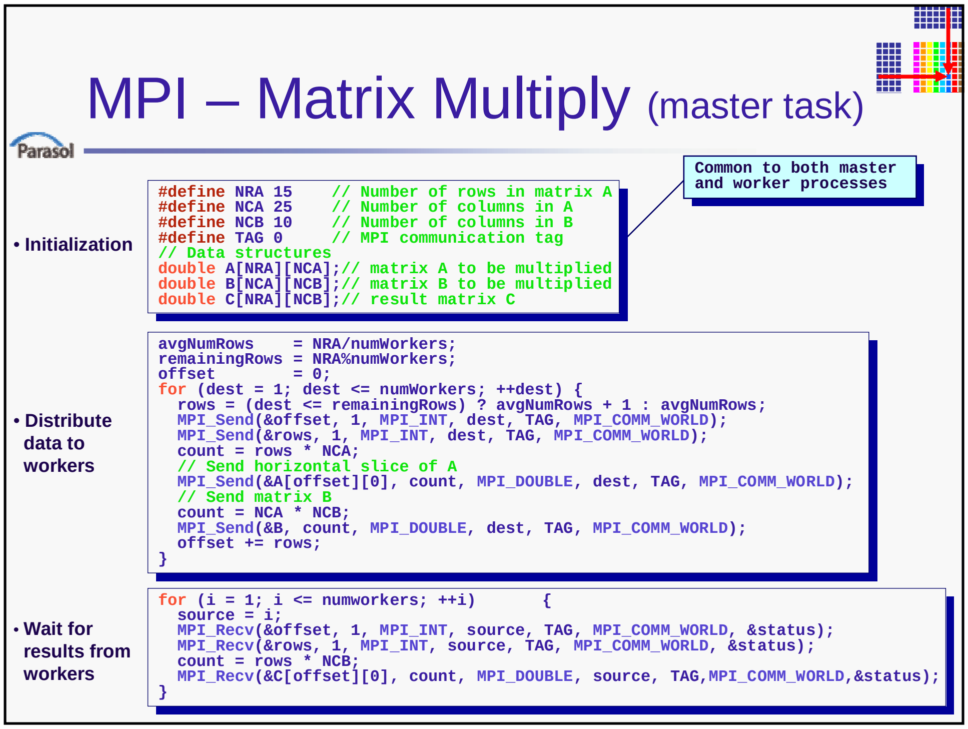


MPI – Collective Communication

Programming Considerations and Restrictions

- Collective operations are blocking
- Collective communication routines do not take message tag arguments
- Collective operations within subsets of processes
  - Partition the subsets into new groups
  - Attach the new groups to new communicators
- Can only be used with MPI predefined data types
  - Not with MPI Derived Data Types

Material from: http://www.llnl.gov/computing/tutorials/mpi/



MPI – Matrix Multiply (master task)

Common to both master and worker processes

- Initialization

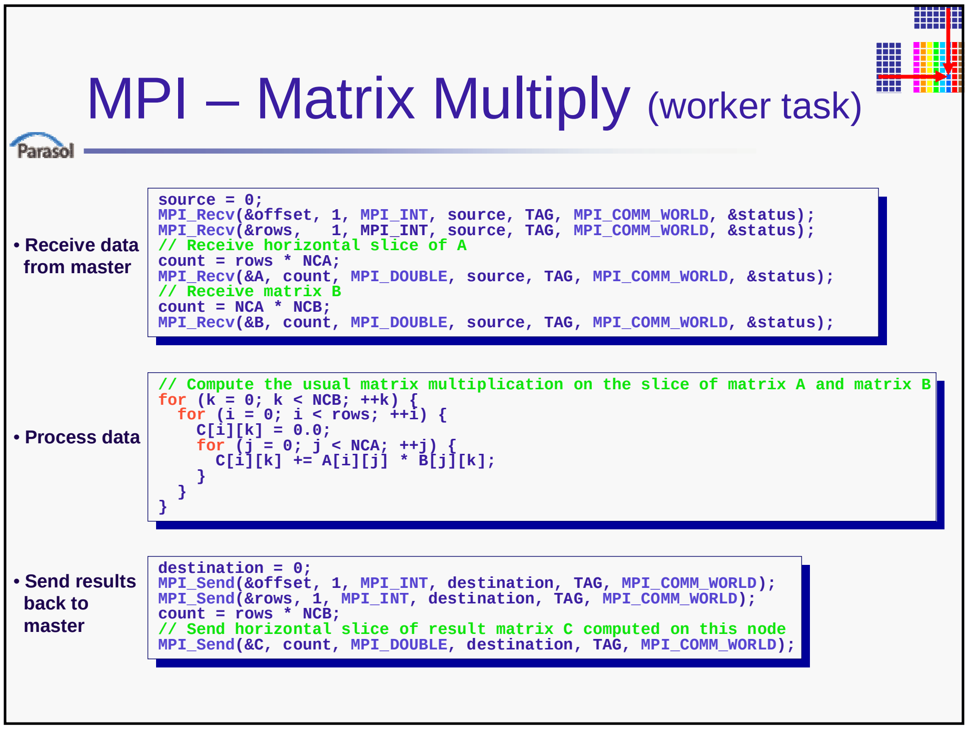
```
#define NRA 15    // Number of rows in matrix A
#define NCA 25    // Number of columns in A
#define NCB 10    // Number of columns in B
#define TAG 0     // MPI communication tag
// Data structures
double A[NRA][NCA];// matrix A to be multiplied
double B[NCA][NCB];// matrix B to be multiplied
double C[NRA][NCB];// result matrix C
```

- Distribute data to workers

```
avgNumRows    = NRA/numWorkers;
remainingRows = NRA%numWorkers;
offset        = 0;
for (dest = 1; dest <= numWorkers; ++dest) {
  rows = (dest <= remainingRows) ? avgNumRows + 1 : avgNumRows;
  MPI_Send(&offset, 1, MPI_INT, dest, TAG, MPI_COMM_WORLD);
  MPI_Send(&rows, 1, MPI_INT, dest, TAG, MPI_COMM_WORLD);
  count = rows * NCA;
  // Send horizontal slice of A
  MPI_Send(&A[offset][0], count, MPI_DOUBLE, dest, TAG, MPI_COMM_WORLD);
  // Send matrix B
  count = NCA * NCB;
  MPI_Send(&B, count, MPI_DOUBLE, dest, TAG, MPI_COMM_WORLD);
  offset += rows;
}
```

- Wait for results from workers

```
for (i = 1; i <= numworkers; ++i)       {
  source = i;
  MPI_Recv(&offset, 1, MPI_INT, source, TAG, MPI_COMM_WORLD, &status);
  MPI_Recv(&rows, 1, MPI_INT, source, TAG, MPI_COMM_WORLD, &status);
  count = rows * NCB;
  MPI_Recv(&C[offset][0], count, MPI_DOUBLE, source, TAG,MPI_COMM_WORLD,&status);
}
```



MPI – Matrix Multiply (worker task)

- Receive data from master

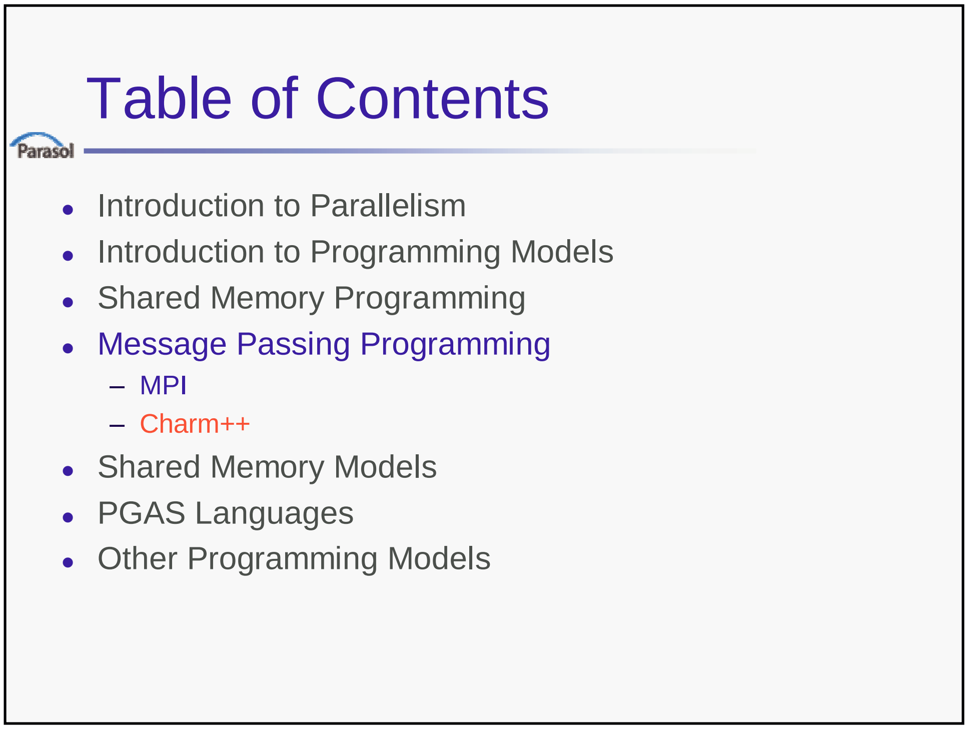
```
source = 0;
MPI_Recv(&offset, 1, MPI_INT, source, TAG, MPI_COMM_WORLD, &status);
MPI_Recv(&rows,   1, MPI_INT, source, TAG, MPI_COMM_WORLD, &status);
// Receive horizontal slice of A
count = rows * NCA;
MPI_Recv(&A, count, MPI_DOUBLE, source, TAG, MPI_COMM_WORLD, &status);
// Receive matrix B
count = NCA * NCB;
MPI_Recv(&B, count, MPI_DOUBLE, source, TAG, MPI_COMM_WORLD, &status);
```

- Process data

```
// Compute the usual matrix multiplication on the slice of matrix A and matrix B
for (k = 0; k < NCB; ++k) {
  for (i = 0; i < rows; ++i) {
    C[i][k] = 0.0;
    for (j = 0; j < NCA; ++j) {
      C[i][k] += A[i][j] * B[j][k];
    }
  }
}
```

- Send results back to master

```
destination = 0;
MPI_Send(&offset, 1, MPI_INT, destination, TAG, MPI_COMM_WORLD);
MPI_Send(&rows, 1, MPI_INT, destination, TAG, MPI_COMM_WORLD);
count = rows * NCB;
// Send horizontal slice of result matrix C computed on this node
MPI_Send(&C, count, MPI_DOUBLE, destination, TAG, MPI_COMM_WORLD);
```



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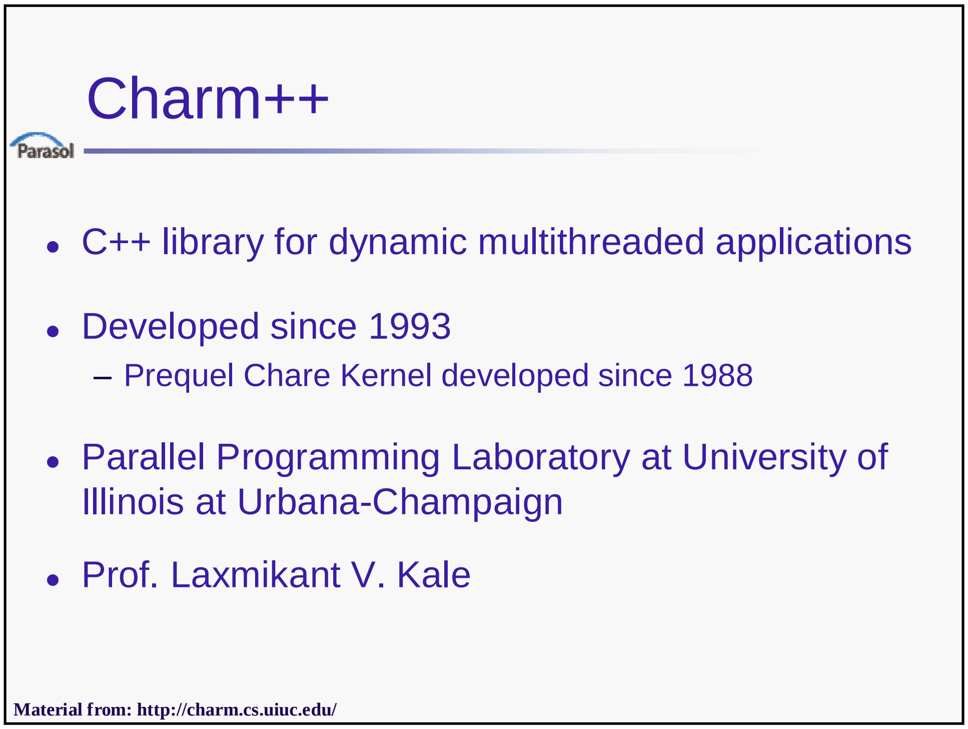
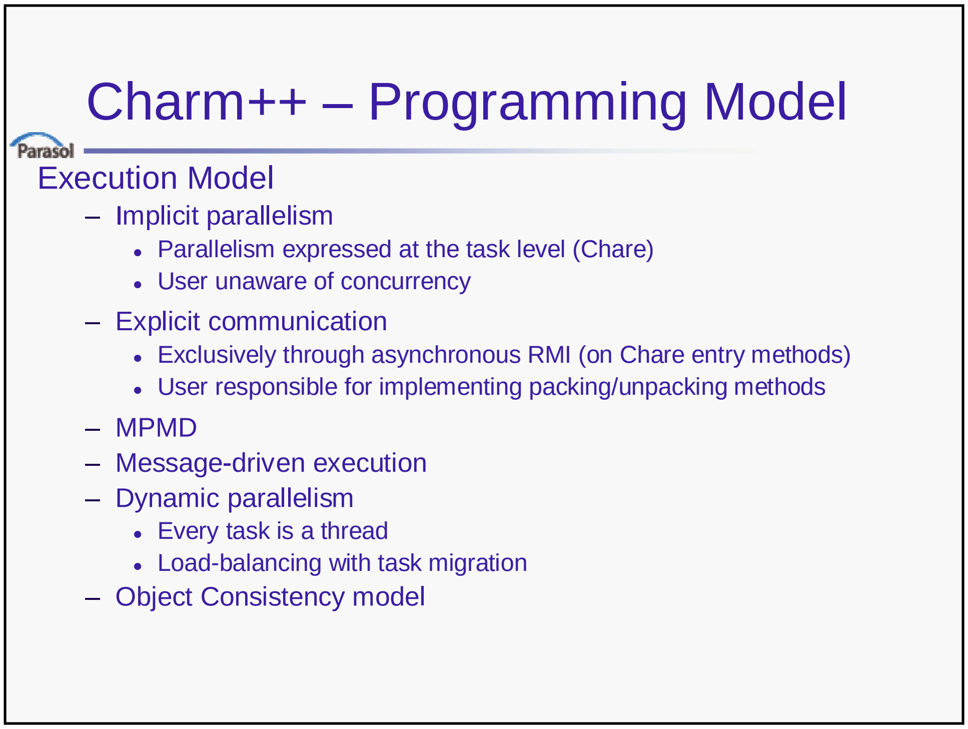


Charm++

- C++ library for dynamic multithreaded applications
- Developed since 1993
  - Prequel Chare Kernel developed since 1988
- Parallel Programming Laboratory at University of Illinois at Urbana-Champaign
- Prof. Laxmikant V. Kale

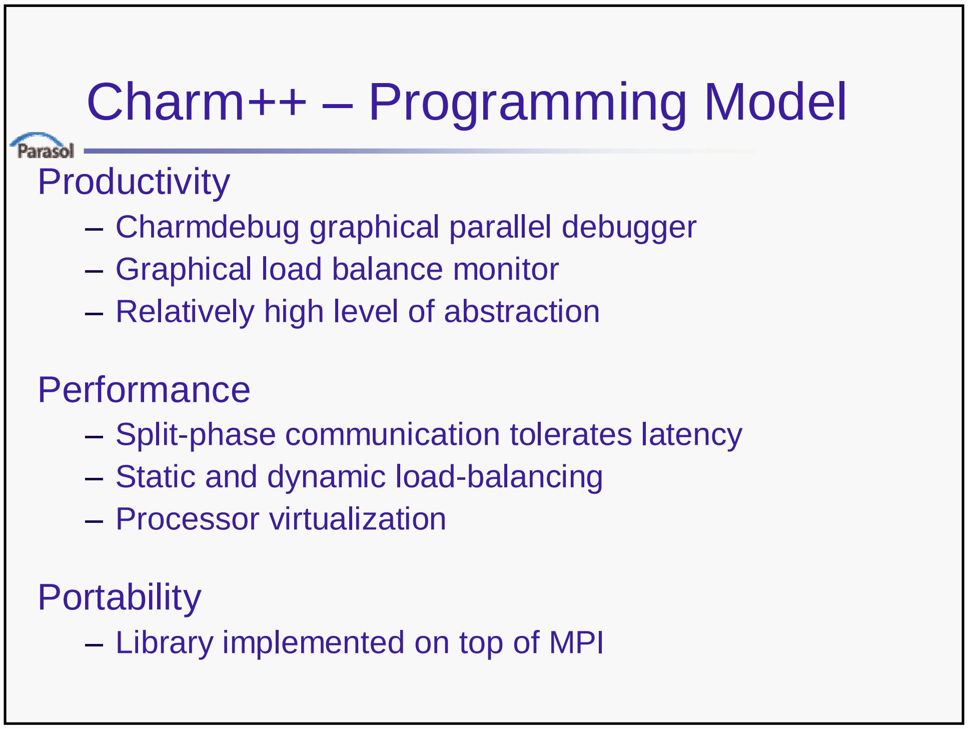
Material from: http://charm.cs.uiuc.edu/



Charm++ – Programming Model

Execution Model

- Implicit parallelism
  - Parallelism expressed at the task level (Chare)
  - User unaware of concurrency
- Explicit communication
  - Exclusively through asynchronous RMI (on Chare entry methods)
  - User responsible for implementing packing/unpacking methods
- MPMD
- Message-driven execution
- Dynamic parallelism
  - Every task is a thread
  - Load-balancing with task migration
- Object Consistency model



Charm++ – Programming Model

Productivity

- Charmdebug graphical parallel debugger
- Graphical load balance monitor
- Relatively high level of abstraction

Performance

- Split-phase communication tolerates latency
- Static and dynamic load-balancing
- Processor virtualization

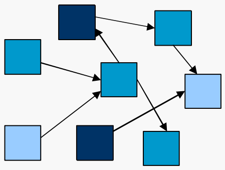
Portability

- Library implemented on top of MPI

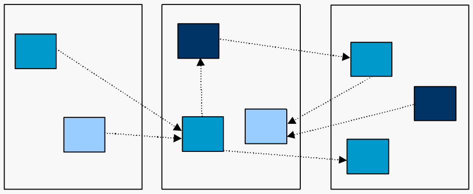
Charm++ – Virtualization

Object-based decomposition

- Divide the computation into a large number of pieces
  - Independent of the number of processors
  - Preferably significantly larger than the number of processors
- Let the system map objects to processors



User view of Chares interaction



System view of Chares mapping

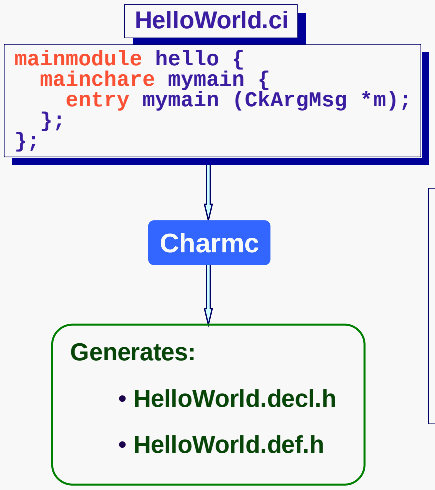
Charm++ – Chares

- Dynamically created on any available processor
- Can be accessed from other processors
  - Chare_ID instead of Thread_ID (virtualization)
- Send messages to each other asynchronously
- Contain entry methods that can be invoked from other Chares

Charm++ – Chares

- User only required to think of the interaction between chares
- Message-driven execution
  - New Chares are only created as “Seed messages”
  - Construction happens when a first message reaches the new Chare

Charm++ – “Hello World”



HelloWorld.ci

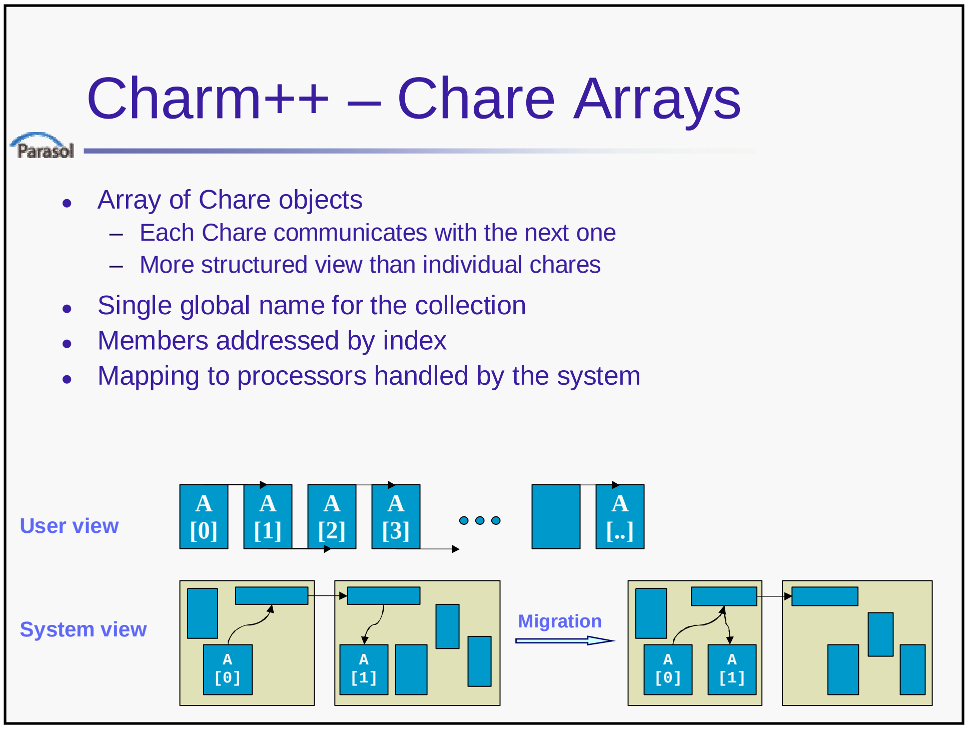
```
mainmodule hello {
  mainchare mymain {
    entry mymain (CkArgMsg *m);
  };
};
```

Generates:

- HelloWorld.decl.h
- HelloWorld.def.h

HelloWorld.C

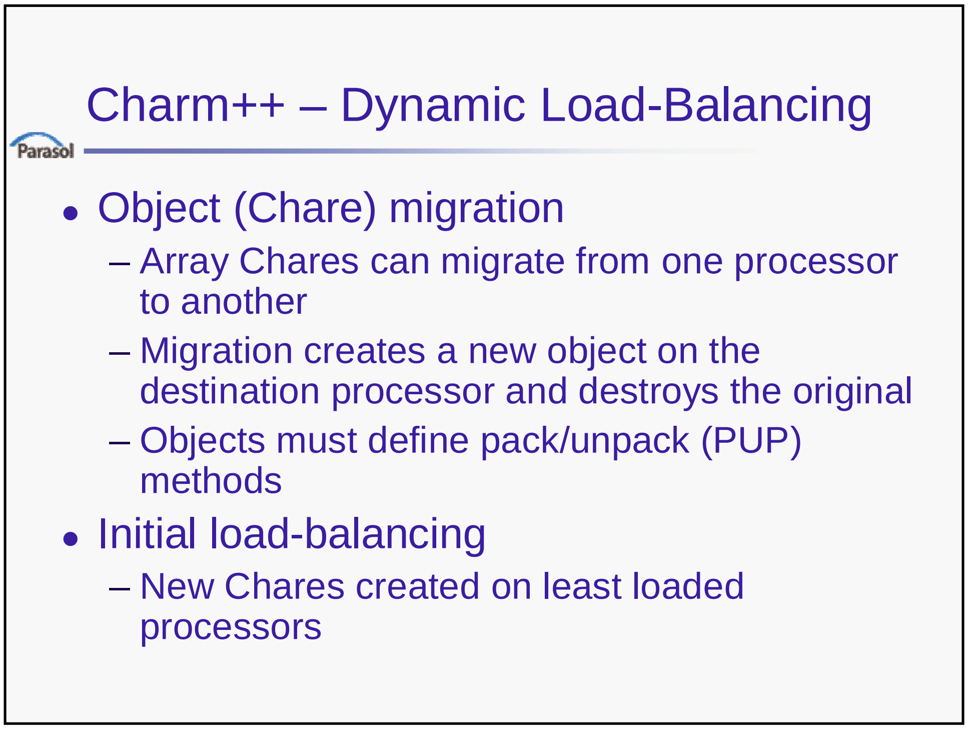
```
#include “HelloWorld.decl.h”

class mymain : public Chare {
public:

  mymain(CkArgMsg *m) {
    ckout << “Hello world !” << endl;
    CkExit();
  }

};
```



Charm++ – Chare Arrays

- Array of Chare objects
  - Each Chare communicates with the next one
  - More structured view than individual chares
- Single global name for the collection
- Members addressed by index
- Mapping to processors handled by the system

User view
A [0]
A [1]
A [2]
A [3]
A [..]
System view
A [0]
A [1]
Migration
A [0]
A [1]



Charm++ – Dynamic Load-Balancing

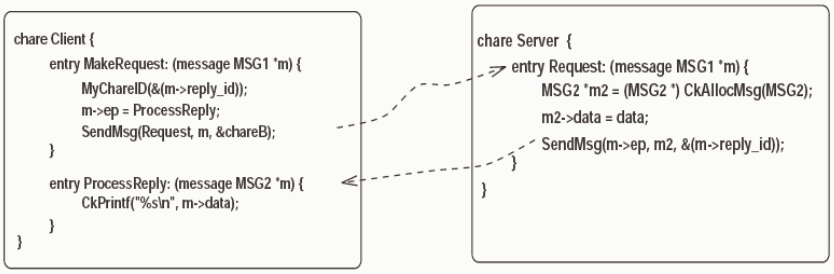
- Object (Chare) migration
  - Array Chares can migrate from one processor to another
  - Migration creates a new object on the destination processor and destroys the original
  - Objects must define pack/unpack (PUP) methods
- Initial load-balancing
  - New Chares created on least loaded processors

Charm++ – Dynamic Load-Balancing

- Centralized load-balancing
  - High-quality balancing with global information
  - High communication cost and latency
- Distributed load-balancing
  - Same principle in small neighborhoods
  - Lower communication cost
  - Global load-imbalance may not be addressed

Charm++ – Split-phase Communication

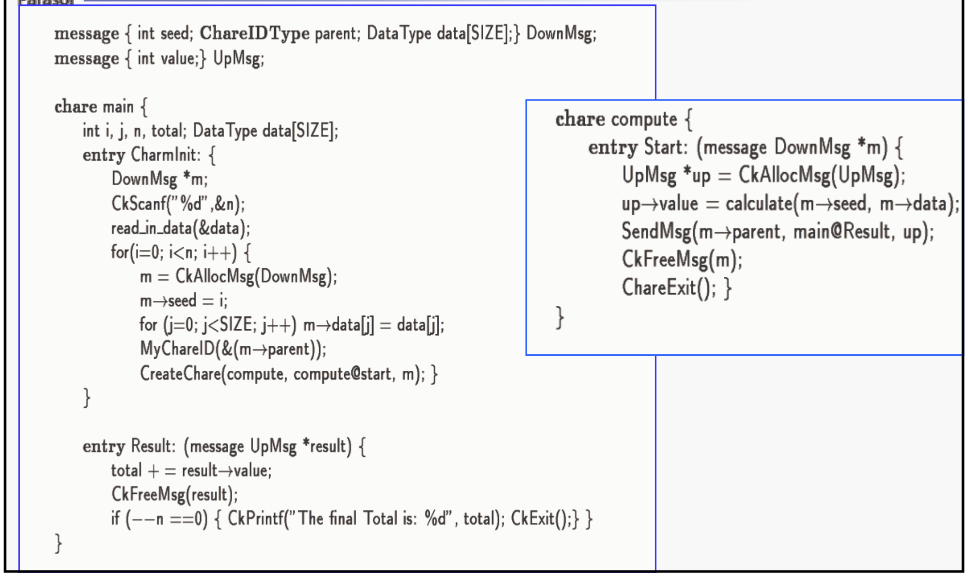
- Asynchronous communication
  - Sender does not block or wait for a return
  - Sender provides callback handler that will process any return value
- Efficient for tolerating latency
  - No explicit waiting for data
  - No stalls with sufficient parallelism



```
chare Client {
    entry MakeRequest: (message MSG1 *m) {
        MyChareID(&(m->reply_id));
        m->ep = ProcessReply;
        SendMsg(Request, m, &chareB);
    }

    entry ProcessReply: (message MSG2 *m) {
        CkPrintf("%s\n", m->data);
    }
}
```

```
chare Server {
    entry Request: (message MSG1 *m) {
        MSG2 *m2 = (MSG2 *) CkAllocMsg(MSG2);
        m2->data = data;
        SendMsg(m->ep, m2, &(m->reply_id));
    }
}
```

Charm++

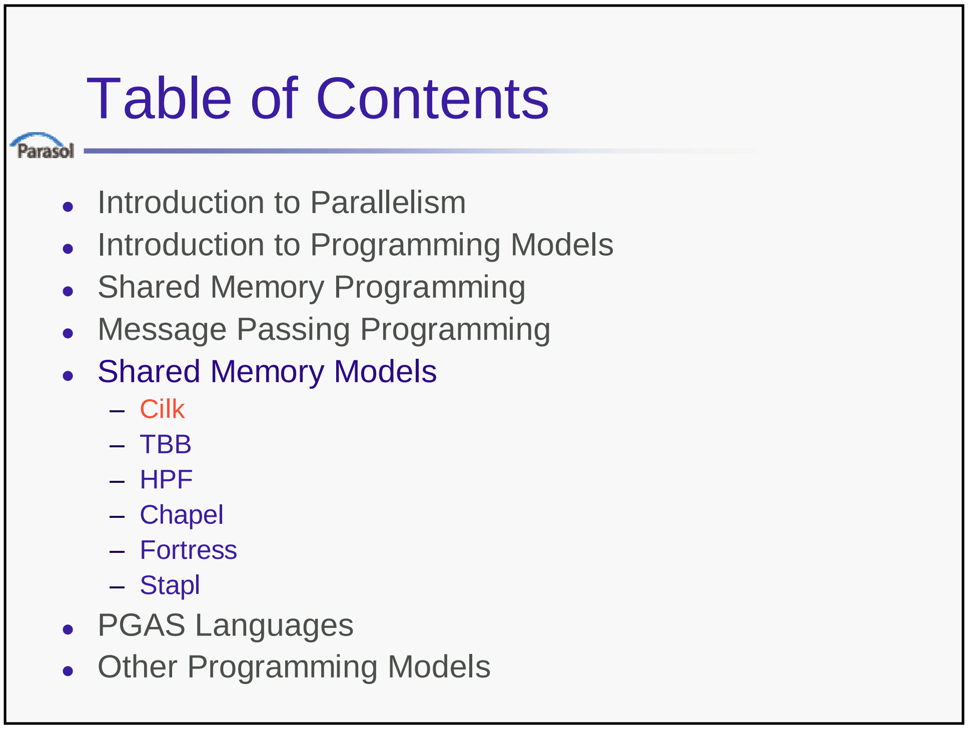


```
message { int seed; ChareIDType parent; DataType data[SIZE];} DownMsg;
message { int value;} UpMsg;

chare main {
    int i, j, n, total; DataType data[SIZE];
    entry CharmInit: {
        DownMsg *m;
        CkScanf("%d",&n);
        read_in_data(&data);
        for(i=0; i<n; i++) {
            m = CkAllocMsg(DownMsg);
            m→seed = i;
            for (j=0; j<SIZE; j++) m→data[j] = data[j];
            MyChareID(&(m→parent));
            CreateChare(compute, compute@start, m); }
    }

    entry Result: (message UpMsg *result) {
        total + = result→value;
        CkFreeMsg(result);
        if (−−n ==0) { CkPrintf("The final Total is: %d", total); CkExit();} }
}
```

```
chare compute {
    entry Start: (message DownMsg *m) {
        UpMsg *up = CkAllocMsg(UpMsg);
        up→value = calculate(m→seed, m→data);
        SendMsg(m→parent, main@Result, up);
        CkFreeMsg(m);
        ChareExit(); }
}
```

References

- MPI
  - http://www.llnl.gov/computing/tutorials/mpi/
  - http://www.mpi-forum.org/
- Charm++
  - http://charm.cs.uiuc.edu/research/charm/
  - http://charm.cs.uiuc.edu/papers/CharmSys1TPDS94.shtml
  - http://charm.cs.uiuc.edu/papers/CharmSys2TPDS94.shtml
  - http://charm.cs.uiuc.edu/manuals/html/charm++/
  - https://agora.cs.uiuc.edu/download/attachments/13044/03_14charmTutorial.ppt
  - http://charm.cs.uiuc.edu/workshops/charmWorkshop2005/slides2005/charm2005_tutorial_charmBasic.ppt



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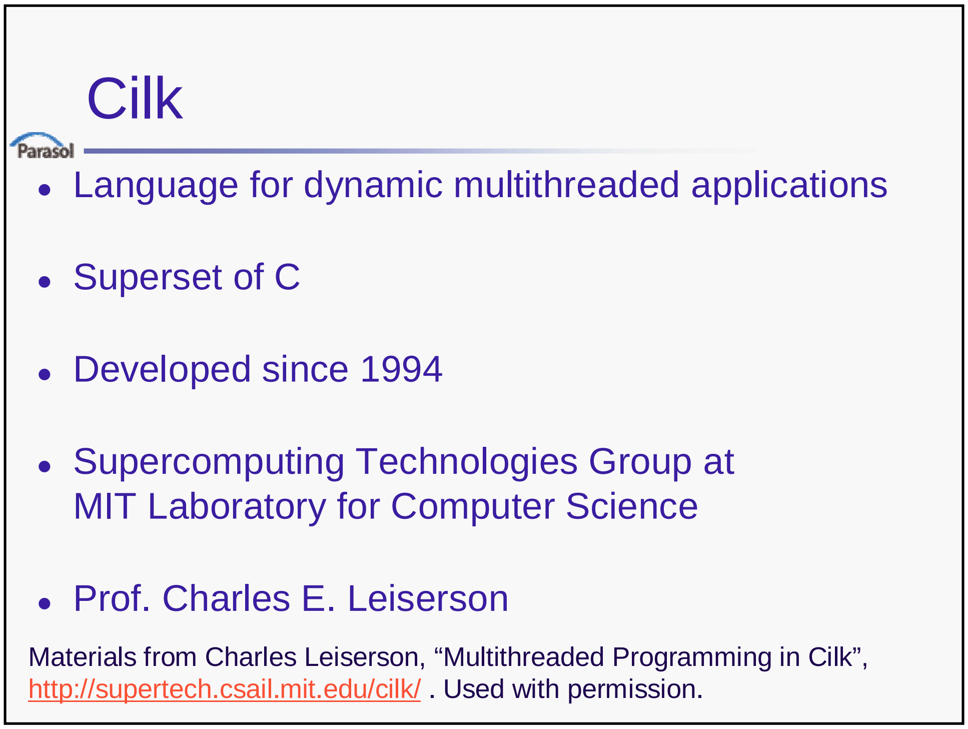
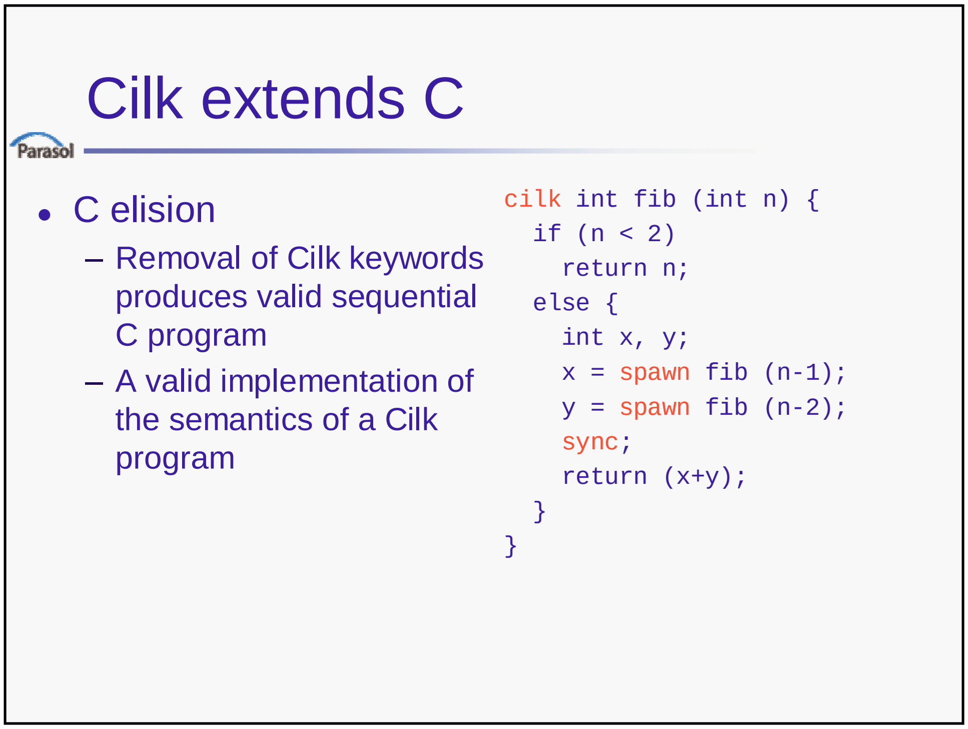


Cilk

- Language for dynamic multithreaded applications
- Superset of C
- Developed since 1994
- Supercomputing Technologies Group at MIT Laboratory for Computer Science
- Prof. Charles E. Leiserson

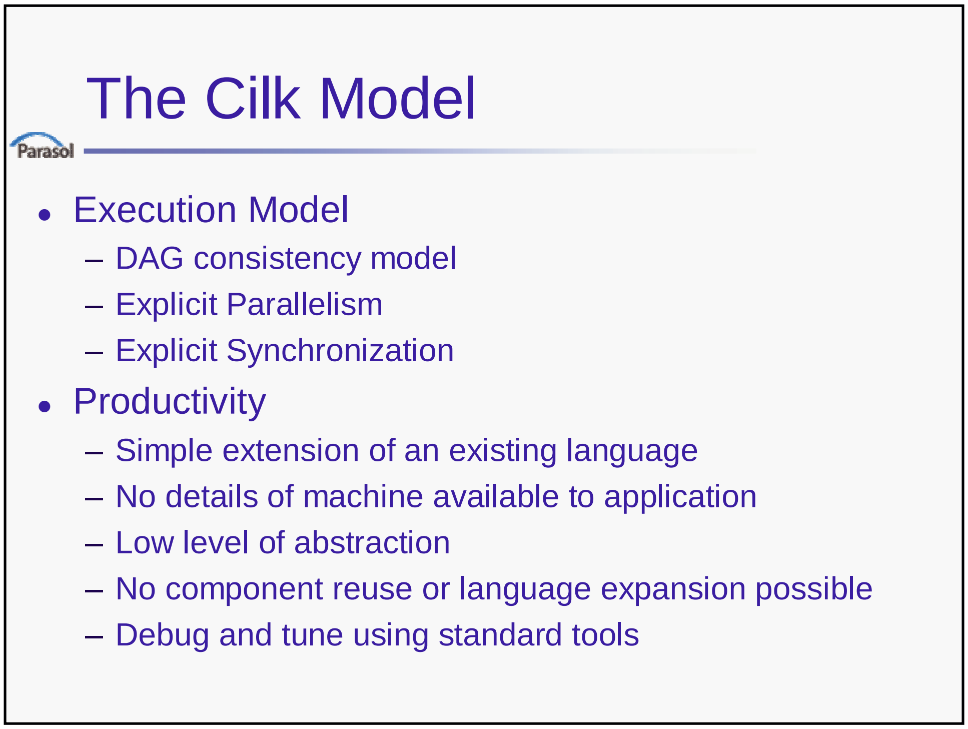
Materials from Charles Leiserson, “Multithreaded Programming in Cilk”, http://supertech.csail.mit.edu/cilk/ . Used with permission.



Cilk extends C

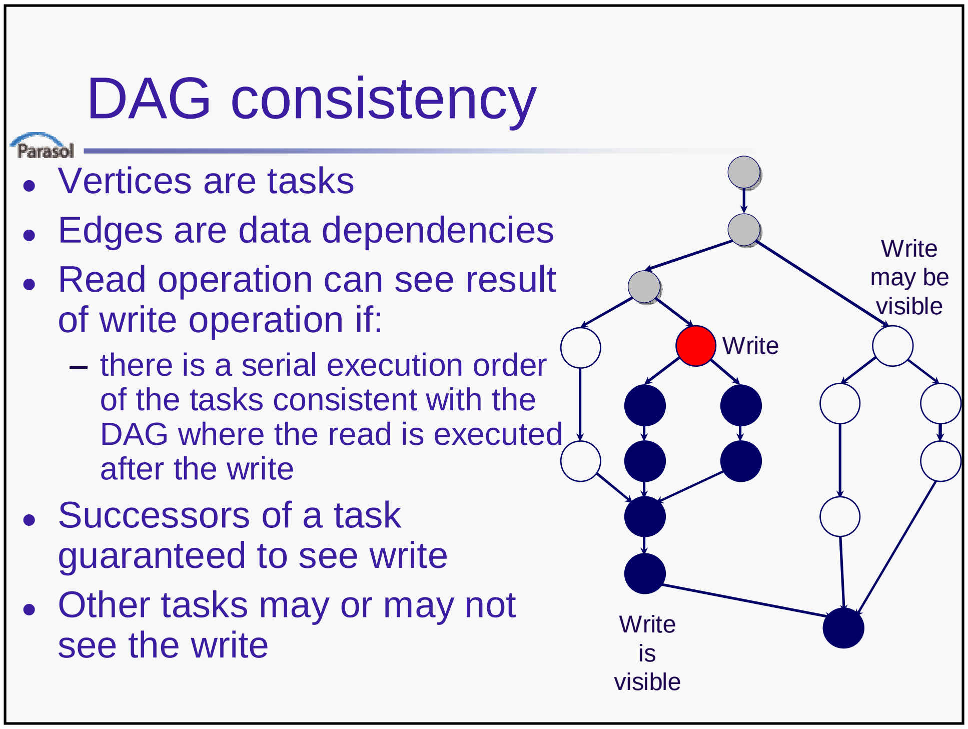
- C elision
  - Removal of Cilk keywords produces valid sequential C program
  - A valid implementation of the semantics of a Cilk program

```
cilk int fib (int n) {
  if (n < 2)
    return n;
  else {
    int x, y;
    x = spawn fib (n-1);
    y = spawn fib (n-2);
    sync;
    return (x+y);
  }
}
```



The Cilk Model

- Execution Model
  - DAG consistency model
  - Explicit Parallelism
  - Explicit Synchronization
- Productivity
  - Simple extension of an existing language
  - No details of machine available to application
  - Low level of abstraction
  - No component reuse or language expansion possible
  - Debug and tune using standard tools



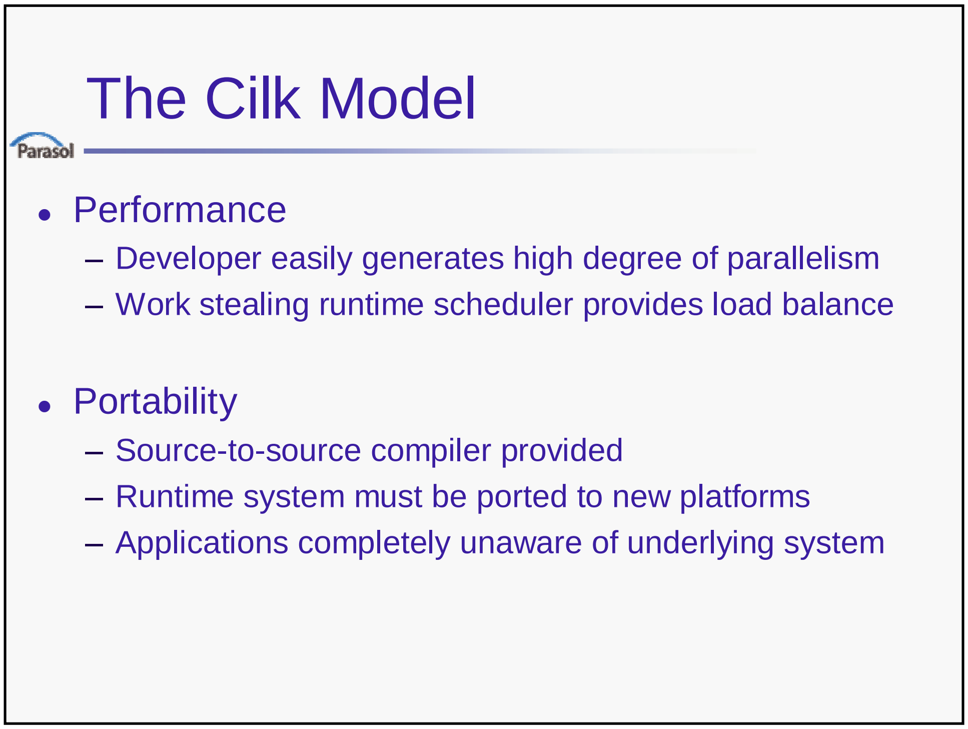
DAG consistency

- Vertices are tasks
- Edges are data dependencies
- Read operation can see result of write operation if:
  - there is a serial execution order of the tasks consistent with the DAG where the read is executed after the write
- Successors of a task guaranteed to see write
- Other tasks may or may not see the write

Write

Write may be visible

Write is visible



The Cilk Model

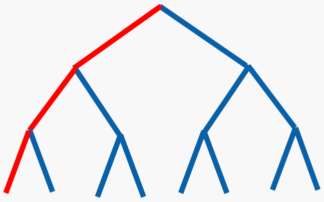
- Performance
  - Developer easily generates high degree of parallelism
  - Work stealing runtime scheduler provides load balance
- Portability
  - Source-to-source compiler provided
  - Runtime system must be ported to new platforms
  - Applications completely unaware of underlying system

Cilk Thread Management

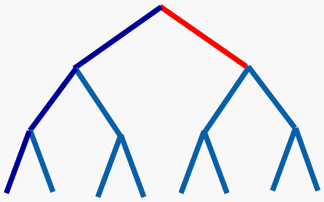
- Application completely unaware of threads
  - Work split into Cilk threads
    - Cilk thread is a task assigned to a processor
    - Tasks scheduled to run on processors by runtime system
    - “Spawn” of Cilk thread is 3-4 times more expensive than C function call
  - Runtime system employs work stealing scheduler

Work Stealing Task Scheduler

- Each processor maintains a deque of tasks
  - Used as a stack
  - Small space usage
  - Excellent cache reuse



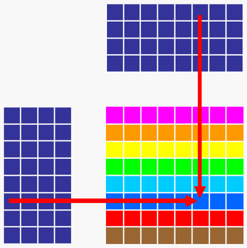
- Processor steals when nothing remains in deque
  - Chooses random victim
  - Treats victim deque as queue
  - Task stolen is usually large



Cilk Synchronization

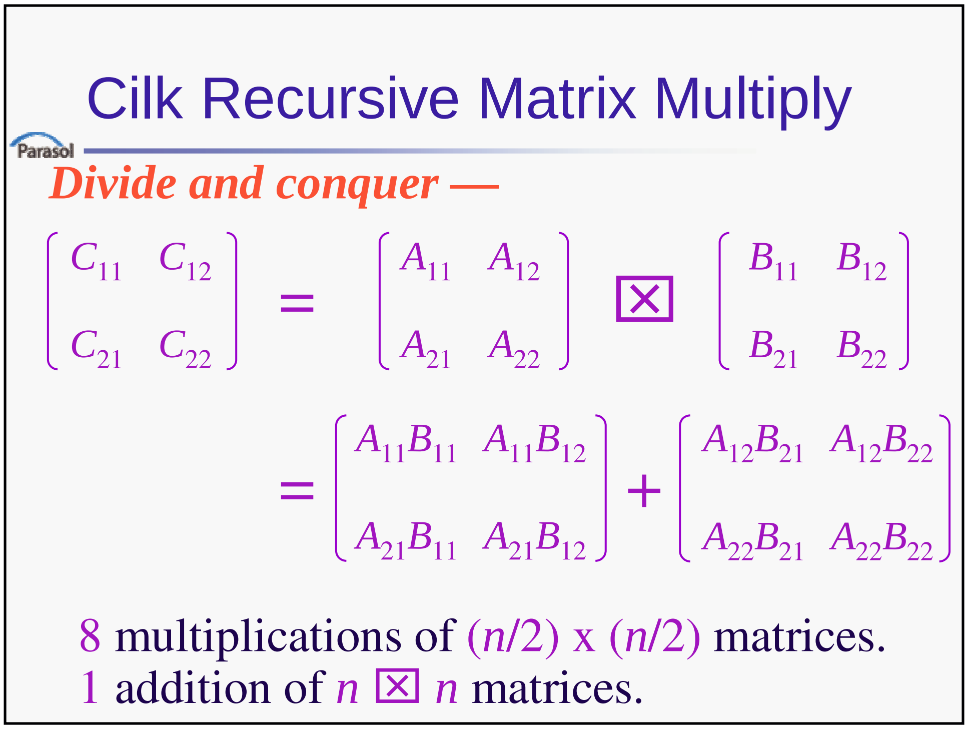
- Cilk_fence()
  - All memory operations of a processor are committed before next instruction is executed.
- Cilk_lockvar variables provide mutual exclusion
  - Cilk_lock attempts to lock and blocks if unsuccessful
  - Cilk_unlock releases lock
  - Locks must be initialized by calling Cilk_lock_init()

Cilk Matrix Multiply



```
cilk void work(*A, *B, *C, i, L, N) {
  for(int j=0; j<N; ++j) {
    for(int k=0; k<L; ++k) {
      C[i][j] +=
          A[i][k]*B[k][j];
    }
  }
}

void matmul(*A, *B, *C, M, L, N) {
  for(int i=0; i<M; ++i) {
    spawn work(A, B, C, i, L, N);
  }
  sync;
}
```



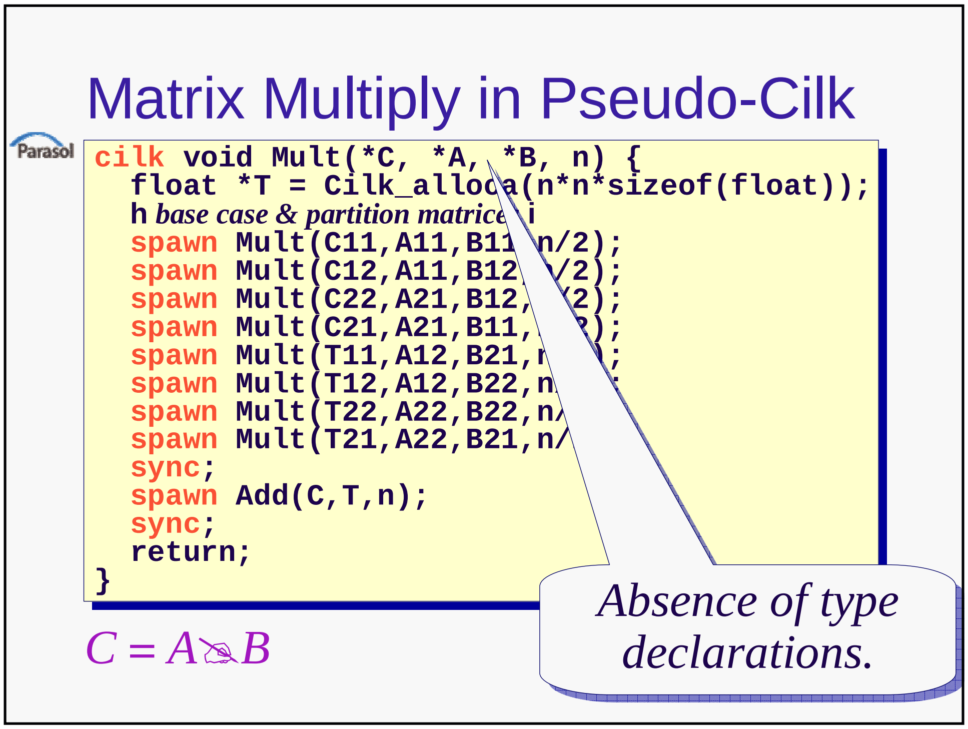
Cilk Recursive Matrix Multiply

Divide and conquer —

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \boxtimes \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

$$= \begin{pmatrix} A_{11}B_{11} & A_{11}B_{12} \\ A_{21}B_{11} & A_{21}B_{12} \end{pmatrix} + \begin{pmatrix} A_{12}B_{21} & A_{12}B_{22} \\ A_{22}B_{21} & A_{22}B_{22} \end{pmatrix}$$

8 multiplications of $(n/2)$ x $(n/2)$ matrices.
1 addition of $n \boxtimes n$ matrices.

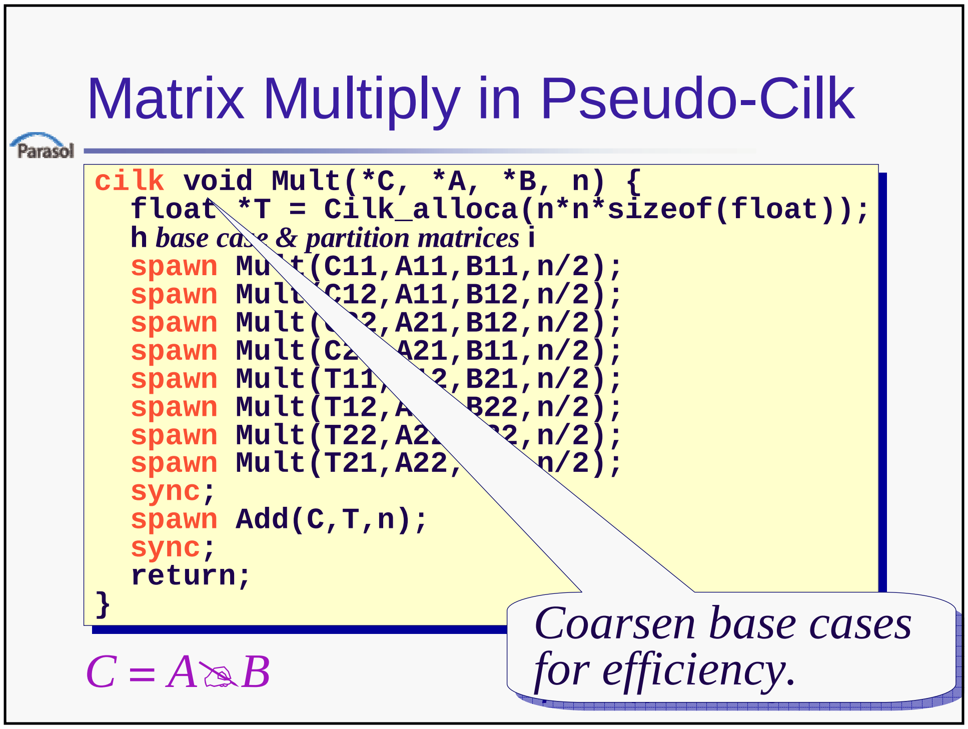


Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A,  *B, n) {
  float *T = Cilk_allo a(n*n*sizeof(float));
  h base case & partition matrice  i
  spawn Mult(C11,A11,B11 n/2);
  spawn Mult(C12,A11,B12, /2);
  spawn Mult(C22,A21,B12,  2);
  spawn Mult(C21,A21,B11,  2);
  spawn Mult(T11,A12,B21,r    ;
  spawn Mult(T12,A12,B22,n/   ;
  spawn Mult(T22,A22,B22,n/
  spawn Mult(T21,A22,B21,n/
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

$C = A ✍ B$

Absence of type declarations.

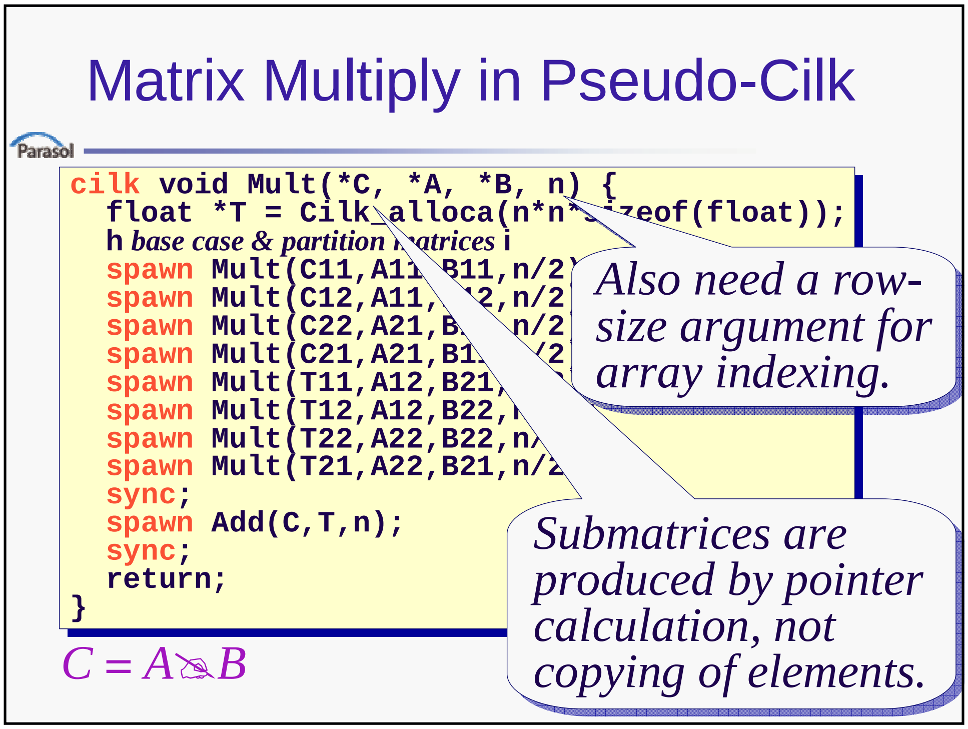


Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A, *B, n) {
  float *T = Cilk_alloca(n*n*sizeof(float));
  ⟨base case & partition matrices⟩
  spawn Mult(C11,A11,B11,n/2);
  spawn Mult(C12,A11,B12,n/2);
  spawn Mult(C22,A21,B12,n/2);
  spawn Mult(C21,A21,B11,n/2);
  spawn Mult(T11,A12,B21,n/2);
  spawn Mult(T12,A12,B22,n/2);
  spawn Mult(T22,A22,B22,n/2);
  spawn Mult(T21,A22,B21,n/2);
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

$C = A \times B$

Coarsen base cases for efficiency.



Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A, *B, n) {
  float *T = Cilk_alloca(n*n*sizeof(float));
  ⟨base case & partition matrices⟩
  spawn Mult(C11,A11,B11,n/2);
  spawn Mult(C12,A11,B12,n/2);
  spawn Mult(C22,A21,B12,n/2);
  spawn Mult(C21,A21,B11,n/2);
  spawn Mult(T11,A12,B21,n/2);
  spawn Mult(T12,A12,B22,n/2);
  spawn Mult(T22,A22,B22,n/2);
  spawn Mult(T21,A22,B21,n/2);
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

$C = A \times B$

Also need a row-size argument for array indexing.

Submatrices are produced by pointer calculation, not copying of elements.

Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A, *B, n) {
  float *T = Cilk_alloca(n*n*sizeof(float));
  h base case & partition matrices i
  spawn Mult(C11,A11,B11,n/2);
  spawn Mult(C12,A11,B12,n/2);
  spawn Mult(C22,A21,B12,n/2);
  spawn Mult(C21,A21,B11,n/2);
  spawn Mult(T11,A12,B21,n/2);
  spawn Mult(T12,A12,B22,n/2);
  spawn Mult(T22,A22,B22,n/2);
  spawn Mult(T21,A22,B21,n/2);
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

$C = A \boxtimes B$

```
cilk void Add(*C, *T, n) {
  h base case & partition matrices i
  spawn Add(C11,T11,n/2);
  spawn Add(C12,T12,n/2);
  spawn Add(C21,T21,n/2);
  spawn Add(C22,T22,n/2);
  sync;
  return;
}
```

$C = C + T$

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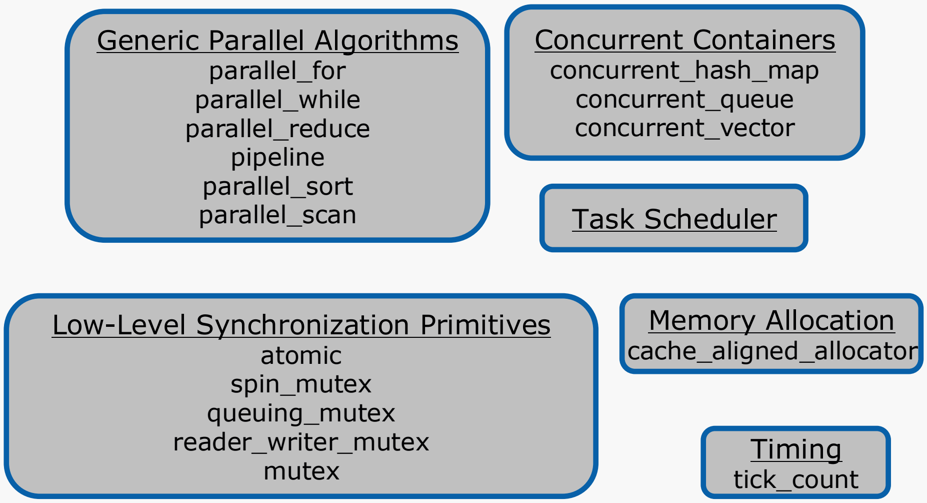
Threading Building Blocks

- C++ library for parallel programming
- STL-like interface for library components
  - **Algorithms** accept **Ranges** that provide access to **Containers**
- Initial release by Intel in August 2006
- Strongly influenced by Cilk, STAPL, and others

Intel® Threading Building Blocks



Generic Parallel Algorithms
parallel_for
parallel_while
parallel_reduce
pipeline
parallel_sort
parallel_scan

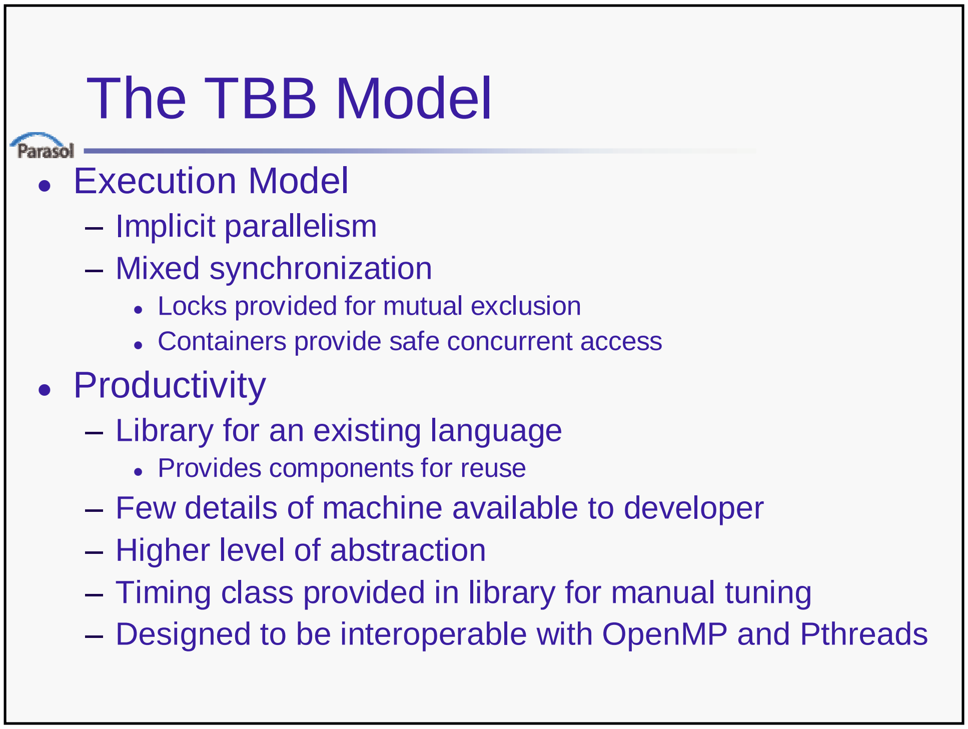
Concurrent Containers
concurrent_hash_map
concurrent_queue
concurrent_vector

Task Scheduler

Low-Level Synchronization Primitives
atomic
spin_mutex
queuing_mutex
reader_writer_mutex
mutex

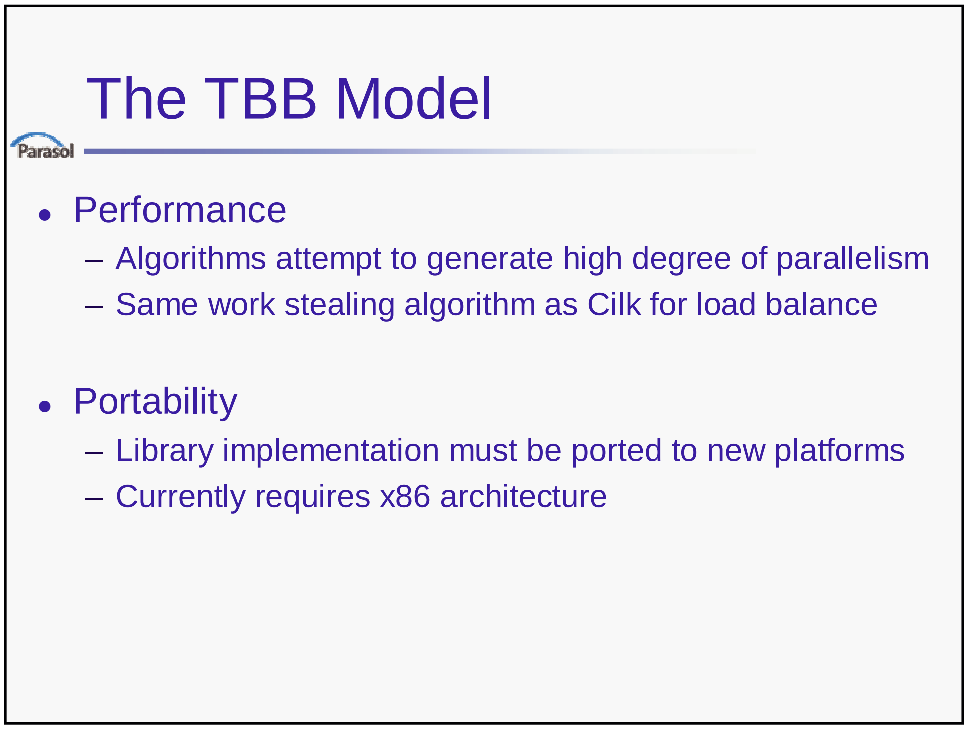
Memory Allocation
cache_aligned_allocator

Timing
tick_count



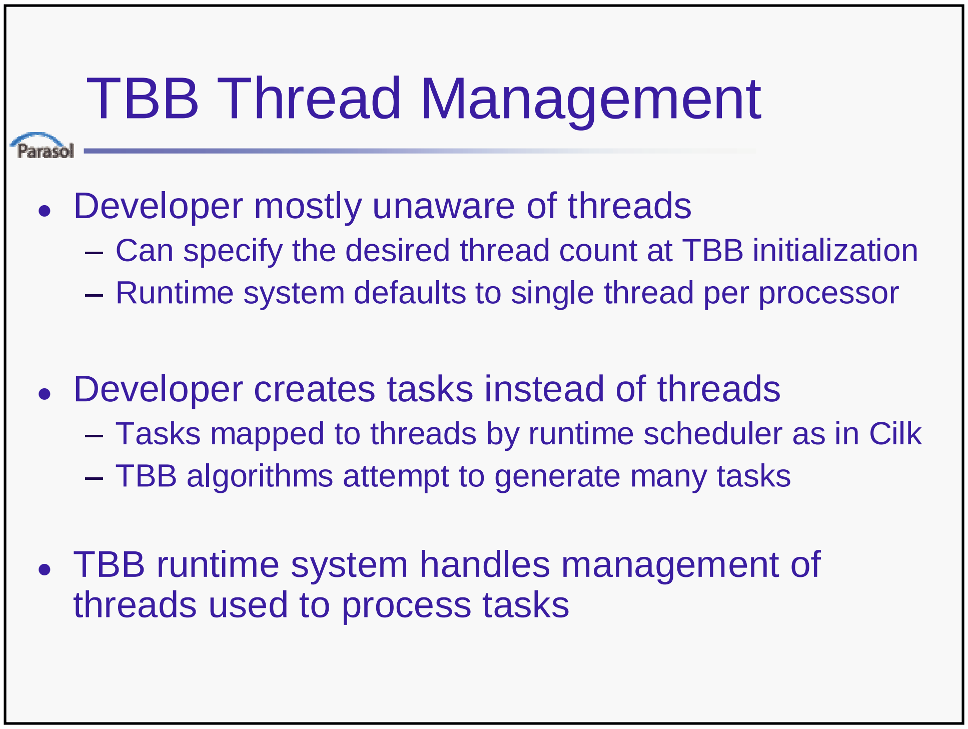
The TBB Model

- Execution Model
  - Implicit parallelism
  - Mixed synchronization
    - Locks provided for mutual exclusion
    - Containers provide safe concurrent access
- Productivity
  - Library for an existing language
    - Provides components for reuse
  - Few details of machine available to developer
  - Higher level of abstraction
  - Timing class provided in library for manual tuning
  - Designed to be interoperable with OpenMP and Pthreads



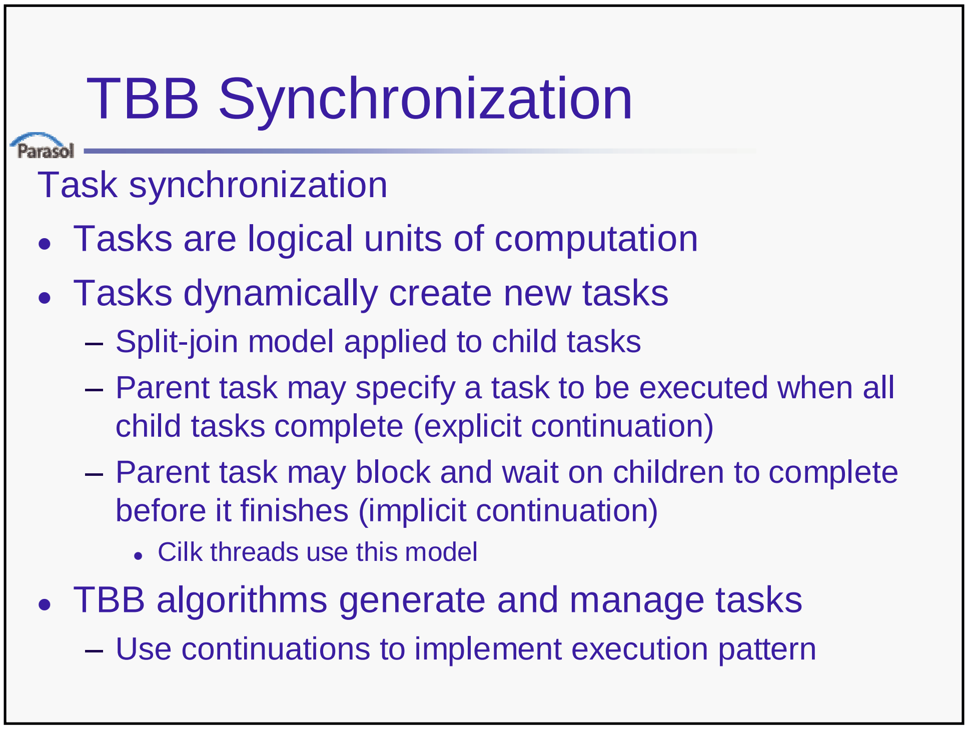
The TBB Model

- Performance
  - Algorithms attempt to generate high degree of parallelism
  - Same work stealing algorithm as Cilk for load balance
- Portability
  - Library implementation must be ported to new platforms
  - Currently requires x86 architecture



TBB Thread Management

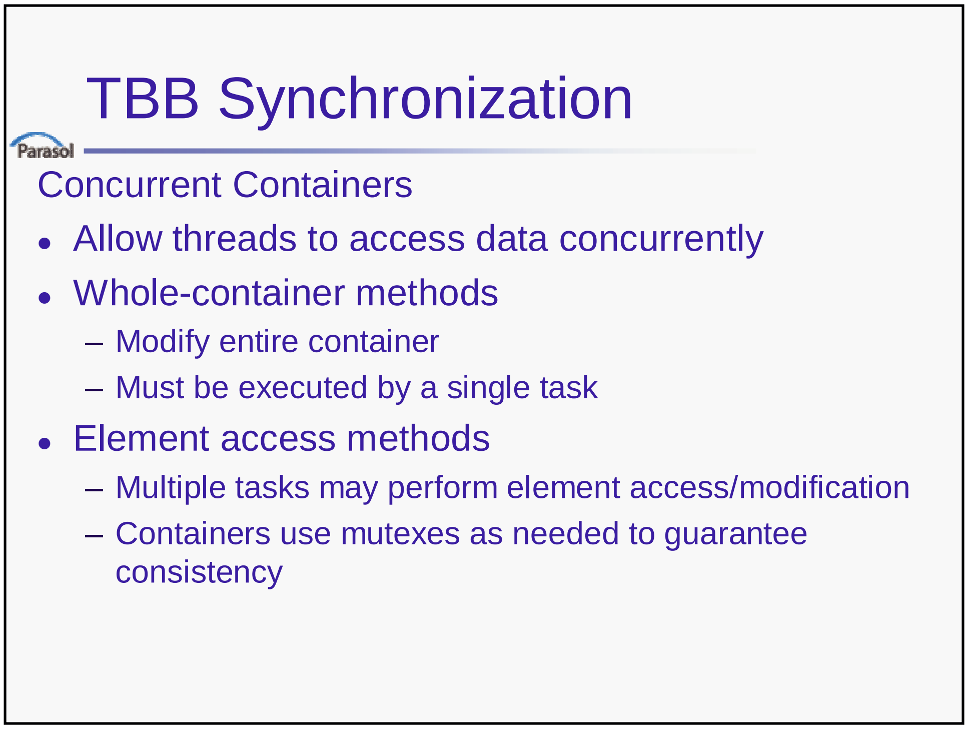
- Developer mostly unaware of threads
  - Can specify the desired thread count at TBB initialization
  - Runtime system defaults to single thread per processor
- Developer creates tasks instead of threads
  - Tasks mapped to threads by runtime scheduler as in Cilk
  - TBB algorithms attempt to generate many tasks
- TBB runtime system handles management of threads used to process tasks



TBB Synchronization

Task synchronization

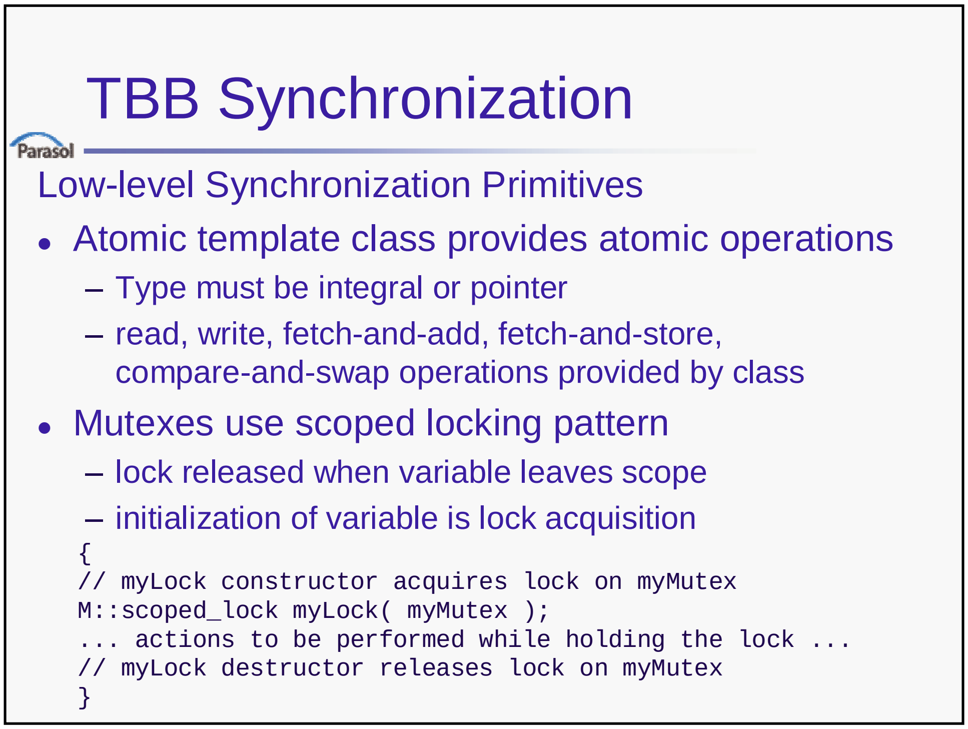
- Tasks are logical units of computation
- Tasks dynamically create new tasks
  - Split-join model applied to child tasks
  - Parent task may specify a task to be executed when all child tasks complete (explicit continuation)
  - Parent task may block and wait on children to complete before it finishes (implicit continuation)
    - Cilk threads use this model
- TBB algorithms generate and manage tasks
  - Use continuations to implement execution pattern



TBB Synchronization

Concurrent Containers

- Allow threads to access data concurrently
- Whole-container methods
  - Modify entire container
  - Must be executed by a single task
- Element access methods
  - Multiple tasks may perform element access/modification
  - Containers use mutexes as needed to guarantee consistency



TBB Synchronization

Low-level Synchronization Primitives

- Atomic template class provides atomic operations
  - Type must be integral or pointer
  - read, write, fetch-and-add, fetch-and-store, compare-and-swap operations provided by class
- Mutexes use scoped locking pattern
  - lock released when variable leaves scope
  - initialization of variable is lock acquisition

```
{
// myLock constructor acquires lock on myMutex
M::scoped_lock myLock( myMutex );
... actions to be performed while holding the lock ...
// myLock destructor releases lock on myMutex
}
```

TBB Synchronization

Low-level Synchronization Primitives

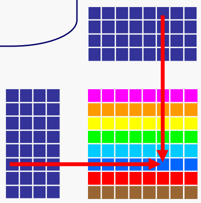
Mutex	Implements mutex concept using underlying OS locks (e.g., pthread mutexes)
Spin Mutex	Thread busy waits until able to acquire lock
Queuing Mutex	Threads acquire lock on mutex in the order they request it.
Reader-Writer Mutex	Multiple threads can hold lock if reading. Writing thread must have exclusive lock on mutex

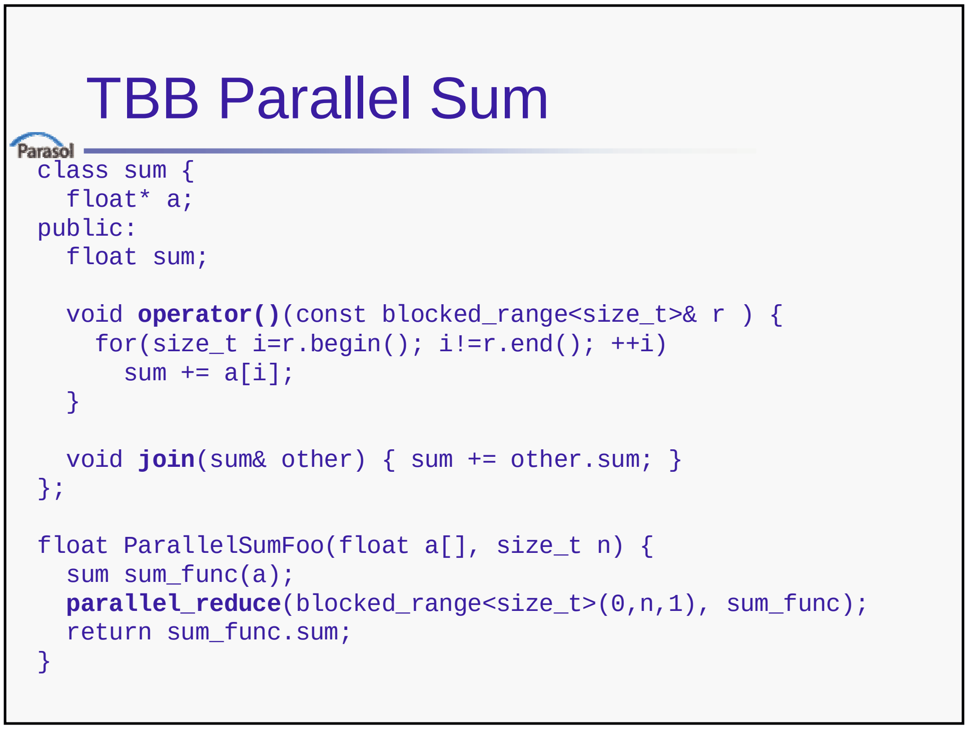
TBB Matrix Multiply

```
class work {
  //data members A,B,C,L,N
public:
  void operator()(const blocked_range<size_t>& r) const {
    for(int i = r.begin(); i != r.end(); ++i) {
      for(int j=0; j<N; ++j) {
        for(int k=0; k<L; ++k) {
          C[i][j] += A[i][k]*B[k][j];
        }
      }
    }
  }
};

task_scheduler_init init;
parallel_for(
  blocked_range<size_t>(0,M,1),
   work(A,B,C,L,M)
);
```

Grainsize parameter determines how many iterations will be executed by a thread at once.





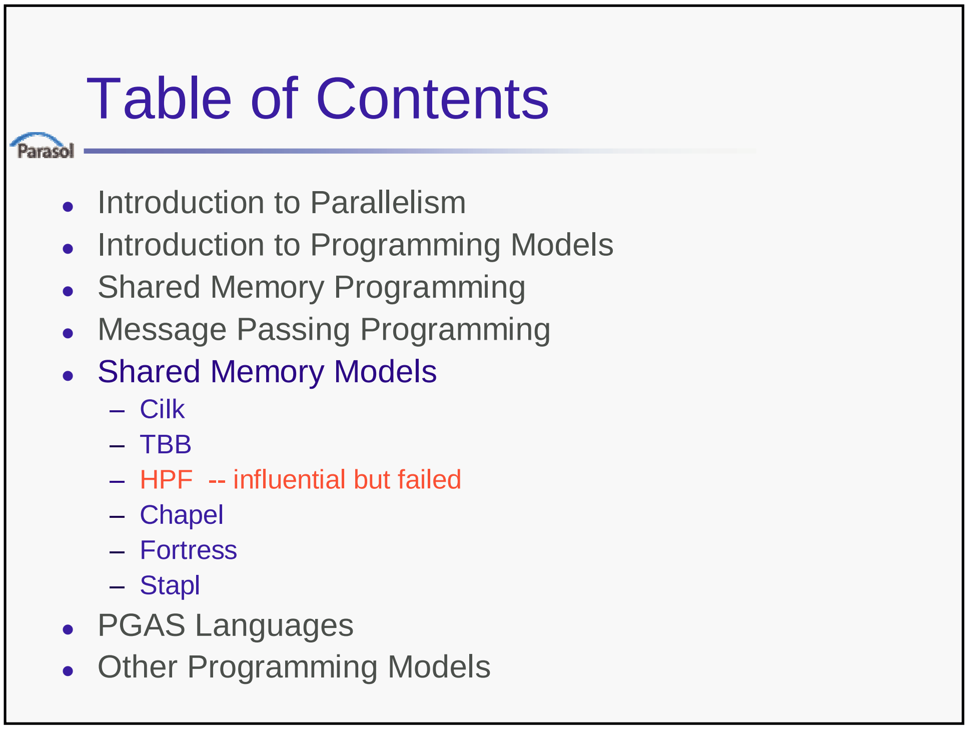
TBB Parallel Sum

```
class sum {
  float* a;
public:
  float sum;

  void operator()(const blocked_range<size_t>& r ) {
    for(size_t i=r.begin(); i!=r.end(); ++i)
      sum += a[i];
  }

  void join(sum& other) { sum += other.sum; }
};

float ParallelSumFoo(float a[], size_t n) {
  sum sum_func(a);
  parallel_reduce(blocked_range<size_t>(0,n,1), sum_func);
  return sum_func.sum;
}
```



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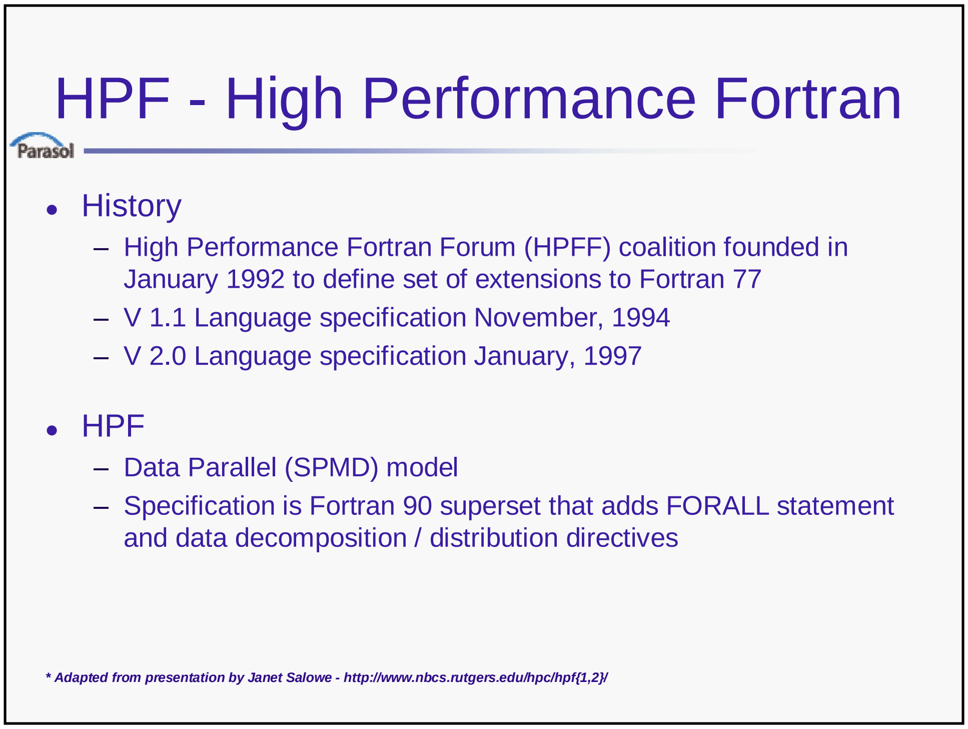
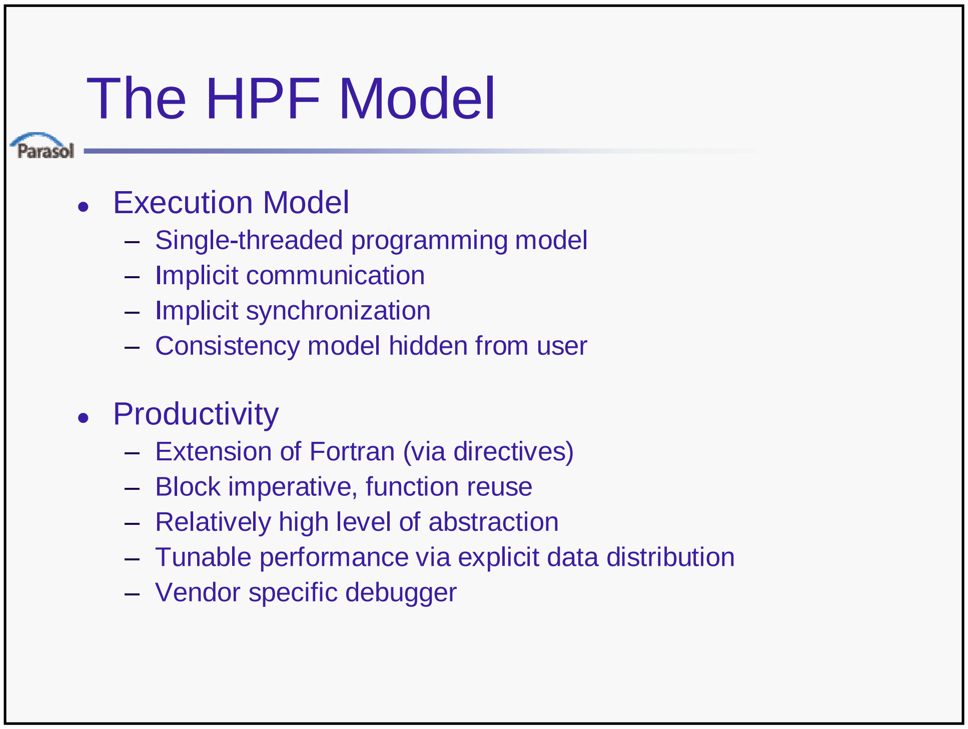


HPF - High Performance Fortran

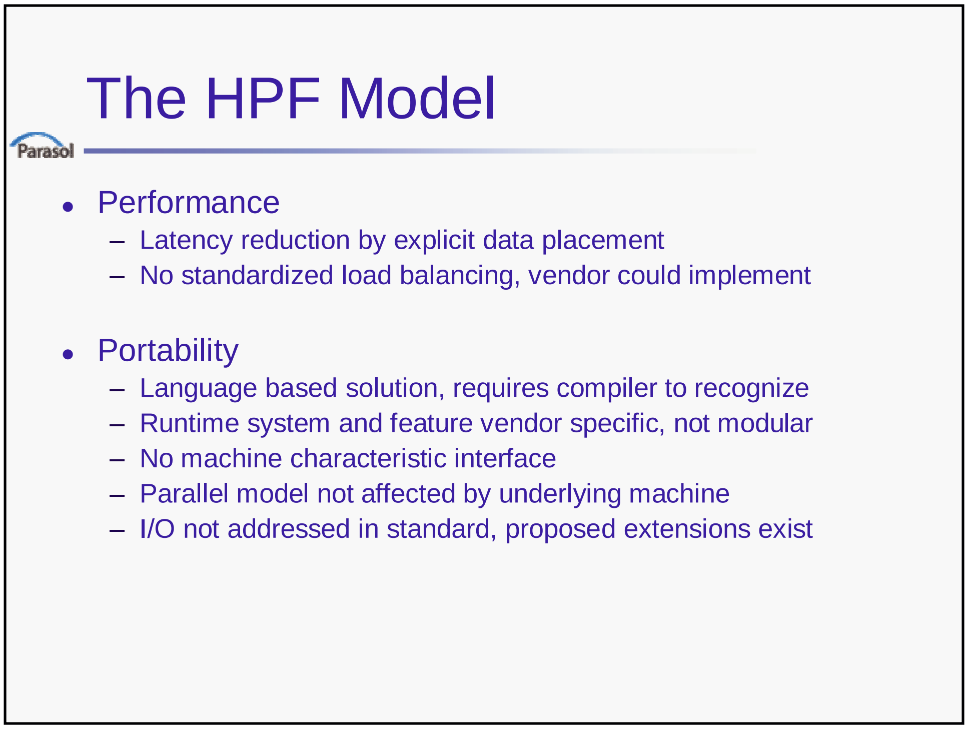
- History
  - High Performance Fortran Forum (HPFF) coalition founded in January 1992 to define set of extensions to Fortran 77
  - V 1.1 Language specification November, 1994
  - V 2.0 Language specification January, 1997
- HPF
  - Data Parallel (SPMD) model
  - Specification is Fortran 90 superset that adds FORALL statement and data decomposition / distribution directives

**** Adapted from presentation by Janet Salowe - http://www.nbcs.rutgers.edu/hpc/hpf{1,2}/***



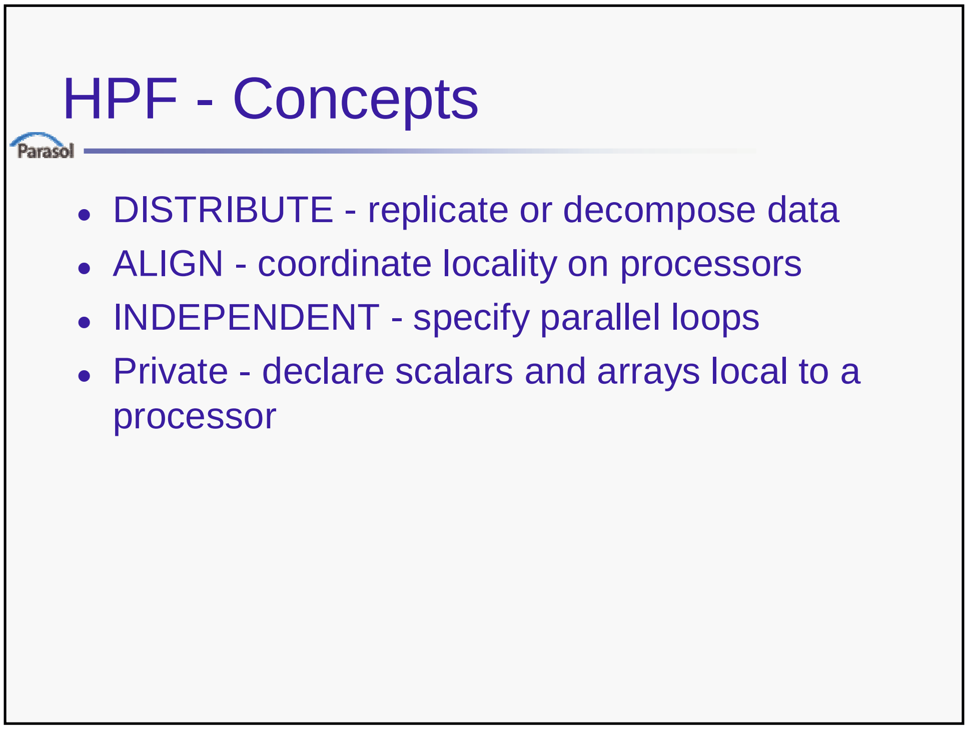
The HPF Model

- Execution Model
  - Single-threaded programming model
  - Implicit communication
  - Implicit synchronization
  - Consistency model hidden from user
- Productivity
  - Extension of Fortran (via directives)
  - Block imperative, function reuse
  - Relatively high level of abstraction
  - Tunable performance via explicit data distribution
  - Vendor specific debugger



The HPF Model

- Performance
  - Latency reduction by explicit data placement
  - No standardized load balancing, vendor could implement
- Portability
  - Language based solution, requires compiler to recognize
  - Runtime system and feature vendor specific, not modular
  - No machine characteristic interface
  - Parallel model not affected by underlying machine
  - I/O not addressed in standard, proposed extensions exist

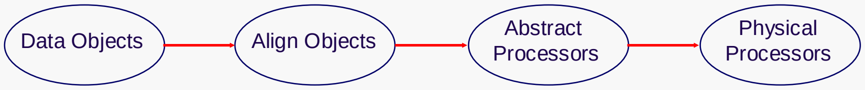


HPF - Concepts

- DISTRIBUTE - replicate or decompose data
- ALIGN - coordinate locality on processors
- INDEPENDENT - specify parallel loops
- Private - declare scalars and arrays local to a processor

Data Mapping Model

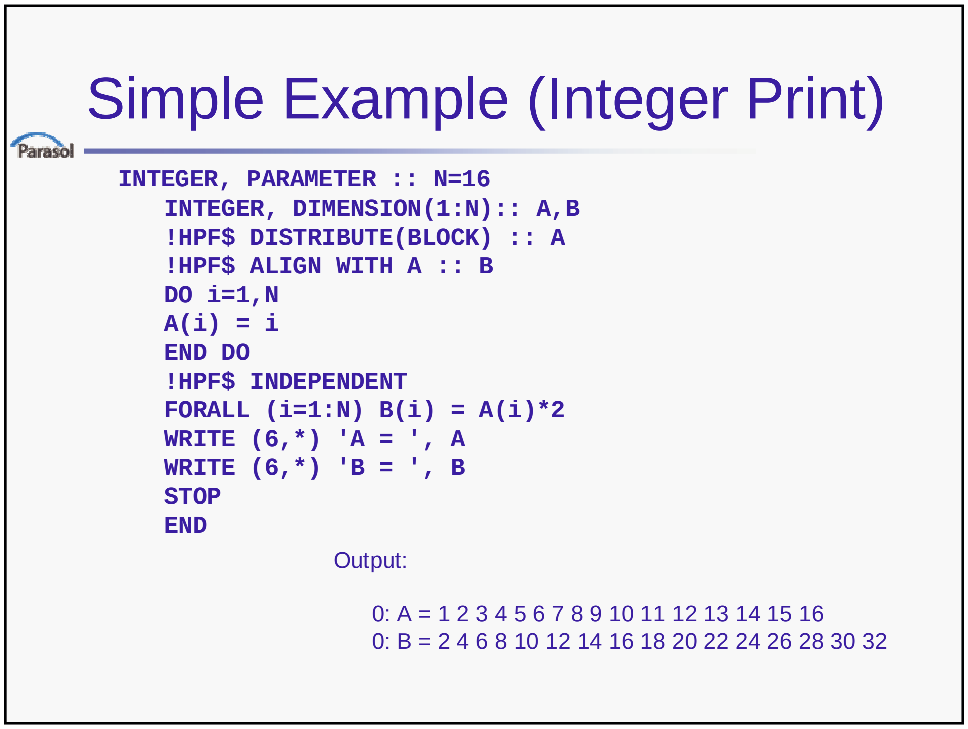
- HPF directives - specify data object allocation
- Goal - minimize communication while maximizing parallelism
- ALIGN - data objects to keep on same processor
- DISTRIBUTE - map aligned object onto processors
- Compiler - implements directives and performs data mapping to physical processors
  - Hides communications, memory details, system specifics



HPF

Ensuring Efficient Execution

- User layout of data
- Good specification to compiler (ALIGN)
- Quality compiler implementation

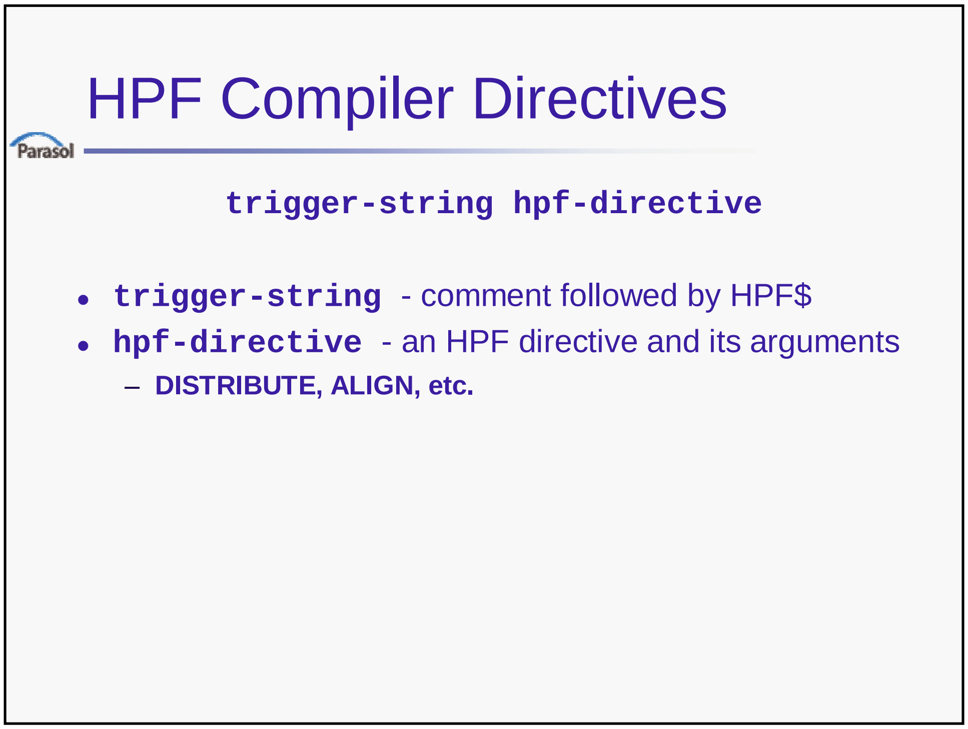


Simple Example (Integer Print)

```
INTEGER, PARAMETER :: N=16
   INTEGER, DIMENSION(1:N):: A,B
   !HPF$ DISTRIBUTE(BLOCK) :: A
   !HPF$ ALIGN WITH A :: B
   DO i=1,N
   A(i) = i
   END DO
   !HPF$ INDEPENDENT
   FORALL (i=1:N) B(i) = A(i)*2
   WRITE (6,*) 'A = ', A
   WRITE (6,*) 'B = ', B
   STOP
   END
```

Output:

```
0: A = 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
0: B = 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
```



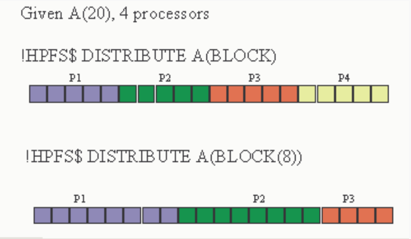
HPF Compiler Directives

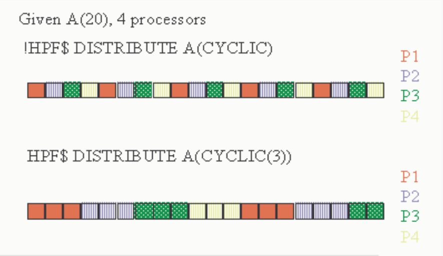
`trigger-string hpf-directive`

- **`trigger-string`** - comment followed by HPF$
- **`hpf-directive`** - an HPF directive and its arguments
  - **DISTRIBUTE, ALIGN, etc.**

HPF - Distribute

- **`!HPF$ DISTRIBUTE object (details)`**
  - – distribution details - comma separated list, for each array dimension
    - BLOCK, BLOCK(N), CYCLIC, CYCLIC(N)
  - – object must be a simple name (e.g., array name)
  - – object can be *aligned to*, but not aligned


Given A(20), 4 processors
!HPFS$ DISTRIBUTE A(BLOCK)
P1
P2
P3
P4
!HPFS$ DISTRIBUTE A(BLOCK(8))
P1
P2
P3


Given A(20), 4 processors
!HPF$ DISTRIBUTE A(CYCLIC)
P1
P2
P3
P4
HPF$ DISTRIBUTE A(CYCLIC(3))
P1
P2
P3
P4

HPF - ALIGN

- **`!HPF$ ALIGN alignee(subscript-list)`**
  `WITH object(subscript-list)`
- **`alignee`** - undistributed, simple object
- **`subscript-list`**
  - – All dimensions
  - – Dummy argument (int constant, variable or expr.)
  - – :
  - – *

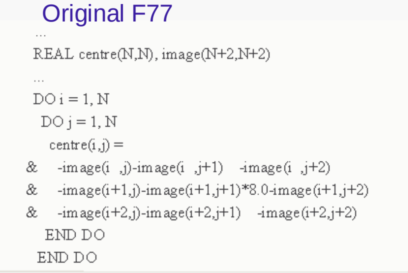
HPF - ALIGN

Equivalent directives, with !HPF$ DISTRIBUTE A(BLOCK,BLOCK)

```
!HPF$ ALIGN B(:,:) WITH A(:,:)
!HPF$ ALIGN (i,j) WITH A(i,j) :: B
!HPF$ ALIGN (:,:) WITH A(:,:) :: B
!HPF$ ALIGN WITH A :: B
```

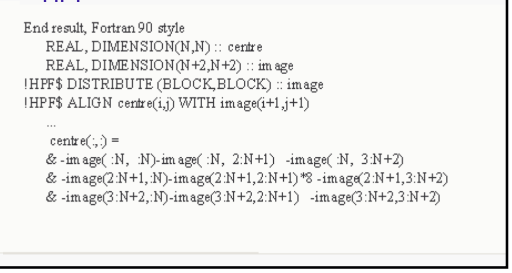
Example

Original F77



```
 ...
 REAL centre(N,N), image(N+2,N+2)
 ...
 DO i = 1, N
  DO j = 1, N
   centre(i,j) =
&    -image(i  ,j)-image(i  ,j+1)   -image(i  ,j+2)
&    -image(i+1,j)-image(i+1,j+1)*8.0-image(i+1,j+2)
&    -image(i+2,j)-image(i+2,j+1)   -image(i+2,j+2)
  END DO
 END DO
```

HPF

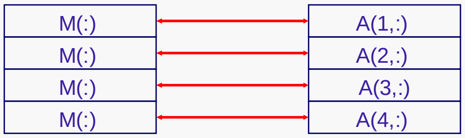


```
End result, Fortran 90 style
   REAL, DIMENSION(N,N) :: centre
   REAL, DIMENSION(N+2,N+2) :: image
!HPF$ DISTRIBUTE (BLOCK,BLOCK) :: image
!HPF$ ALIGN centre(i,j) WITH image(i+1,j+1)
   ...
    centre(:,:) =
   & -image( :N,  :N)-image( :N,  2:N+1)  -image( :N,  3:N+2)
   & -image(2:N+1,:N)-image(2:N+1,2:N+1)*8 -image(2:N+1,3:N+2)
   & -image(3:N+2,:N)-image(3:N+2,2:N+1)  -image(3:N+2,3:N+2)
```

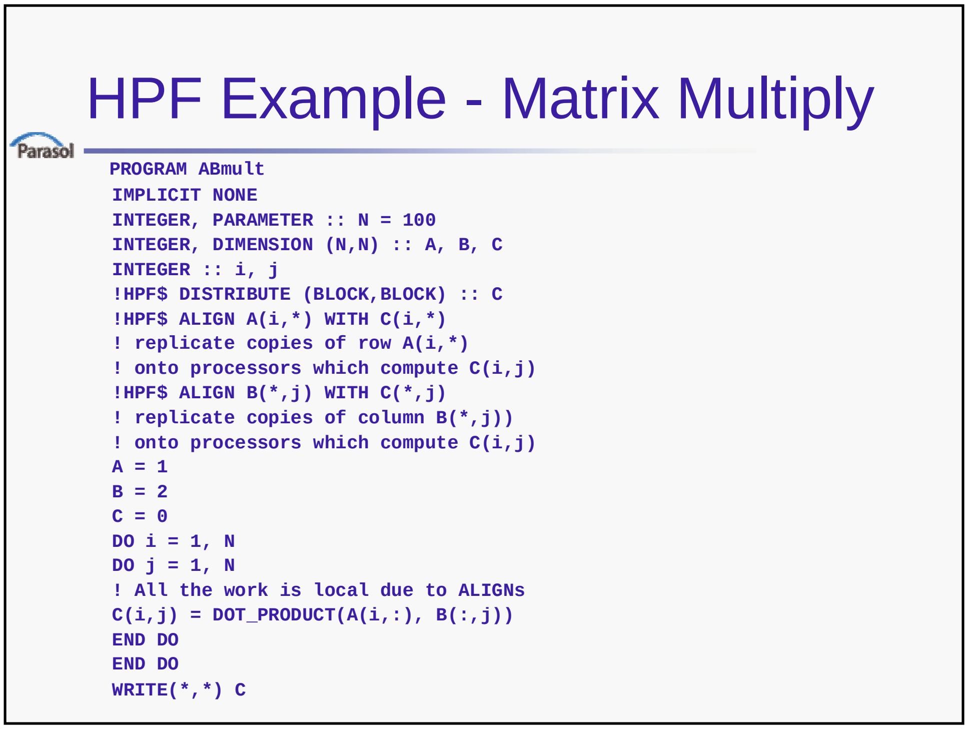
HPF - Alignment for Replication

- Replicate heavily read arrays, such as lookup tables, to reduce communication
  - Use when memory is cheaper than communication
  - If replicated data is updated, compiler updates ALL copies
- If array M is used with every element of A:

```
INTEGER M(4)
INTEGER A(4,5)
!HPF$ ALIGN M(*) WITH A(i,*)
```



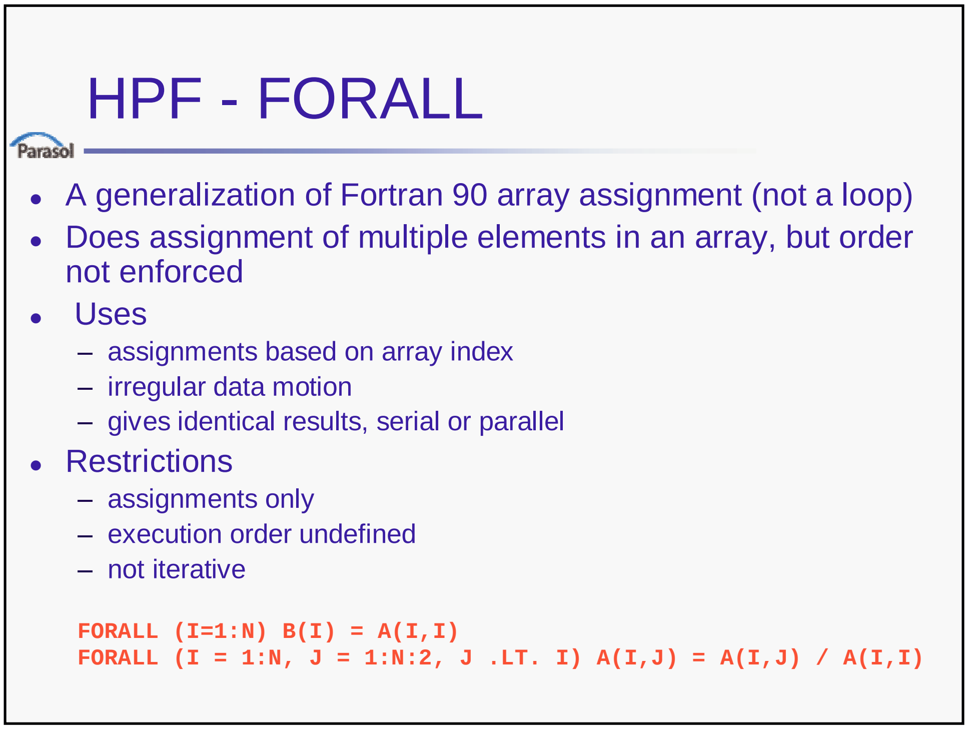
M(:)	A(1,:)
M(:)	A(2,:)
M(:)	A(3,:)
M(:)	A(4,:)



HPF Example - Matrix Multiply

Parasol

```
PROGRAM ABmult
IMPLICIT NONE
INTEGER, PARAMETER :: N = 100
INTEGER, DIMENSION (N,N) :: A, B, C
INTEGER :: i, j
!HPF$ DISTRIBUTE (BLOCK,BLOCK) :: C
!HPF$ ALIGN A(i,*) WITH C(i,*)
! replicate copies of row A(i,*)
! onto processors which compute C(i,j)
!HPF$ ALIGN B(*,j) WITH C(*,j)
! replicate copies of column B(*,j))
! onto processors which compute C(i,j)
A = 1
B = 2
C = 0
DO i = 1, N
DO j = 1, N
! All the work is local due to ALIGNs
C(i,j) = DOT_PRODUCT(A(i,:), B(:,j))
END DO
END DO
WRITE(*,*) C
```

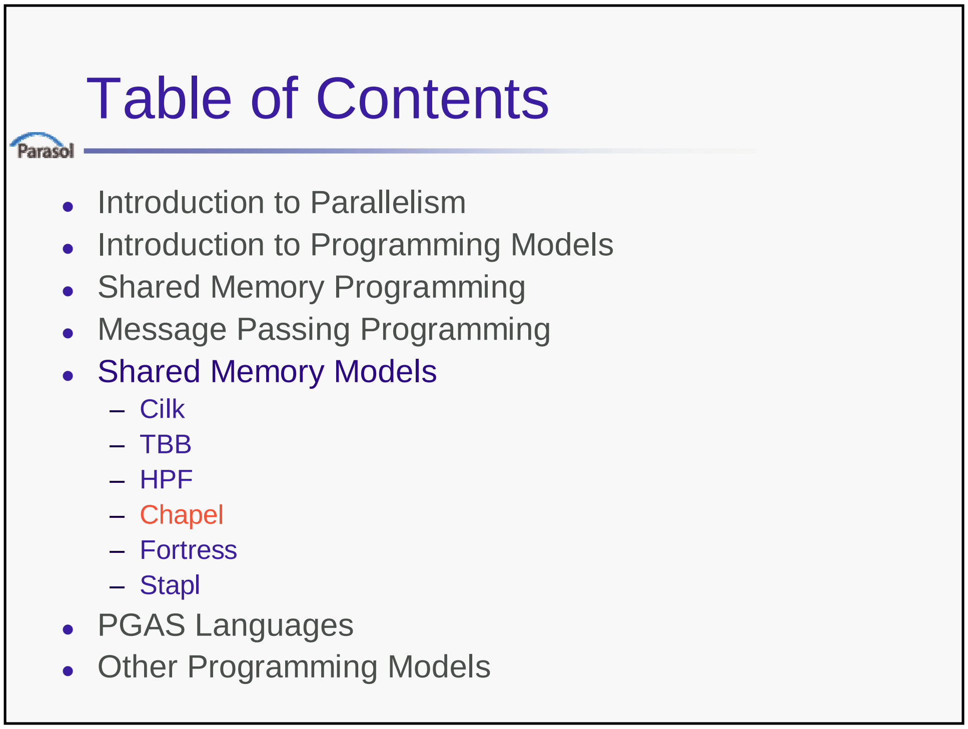


HPF - FORALL

Parasol

- A generalization of Fortran 90 array assignment (not a loop)
- Does assignment of multiple elements in an array, but order not enforced
- Uses
  - assignments based on array index
  - irregular data motion
  - gives identical results, serial or parallel
- Restrictions
  - assignments only
  - execution order undefined
  - not iterative

```
FORALL (I=1:N) B(I) = A(I,I)
FORALL (I = 1:N, J = 1:N:2, J .LT. I) A(I,J) = A(I,J) / A(I,I)
```



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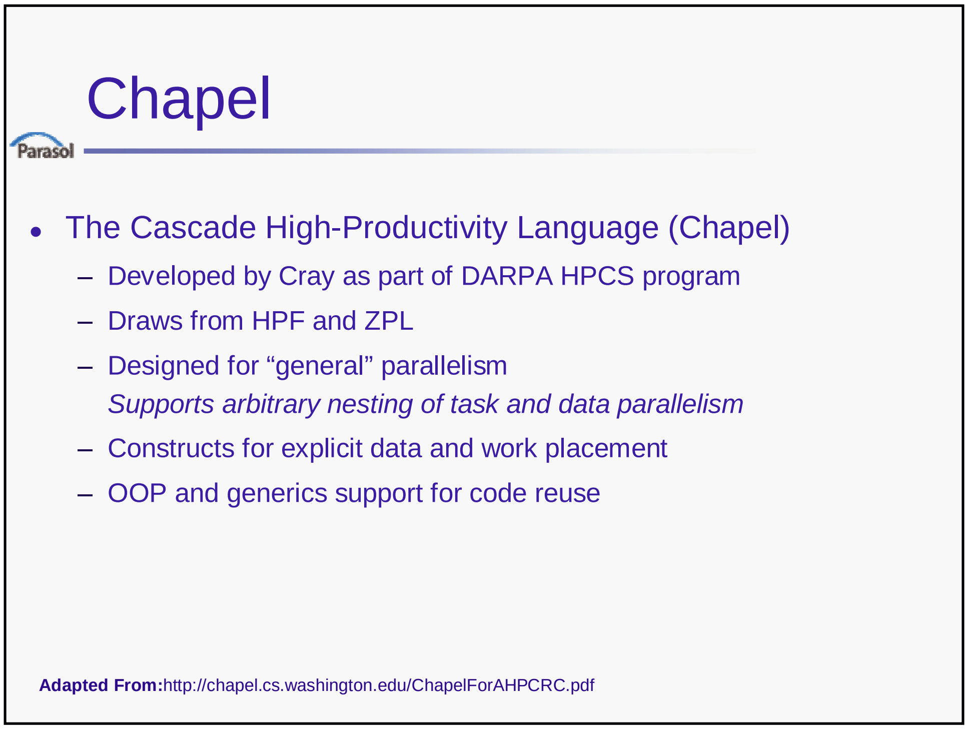
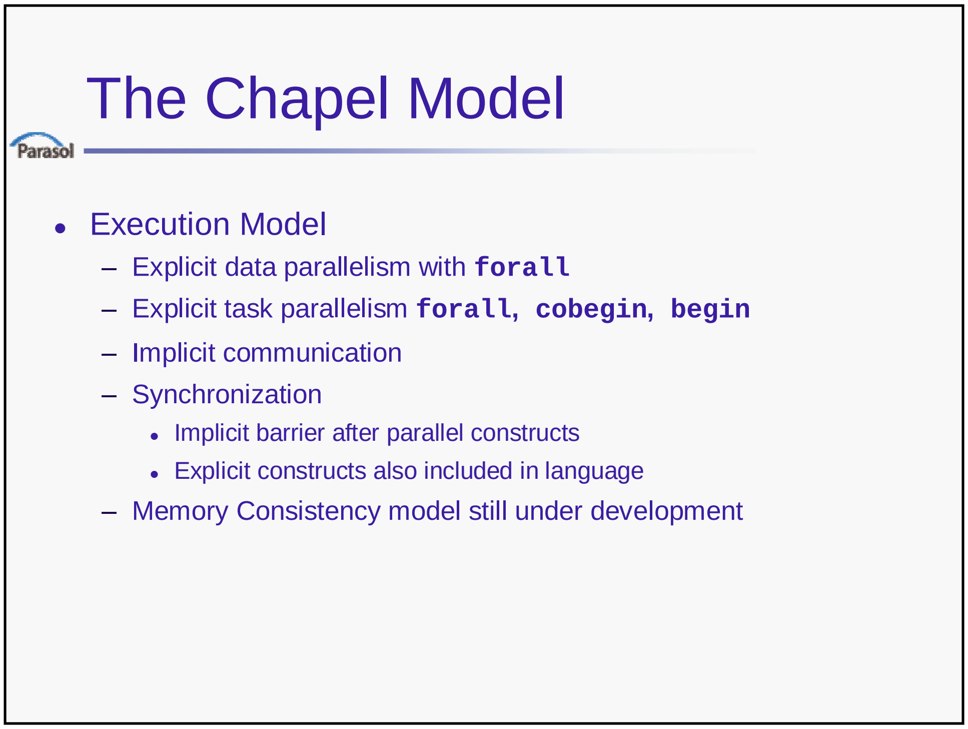


Chapel

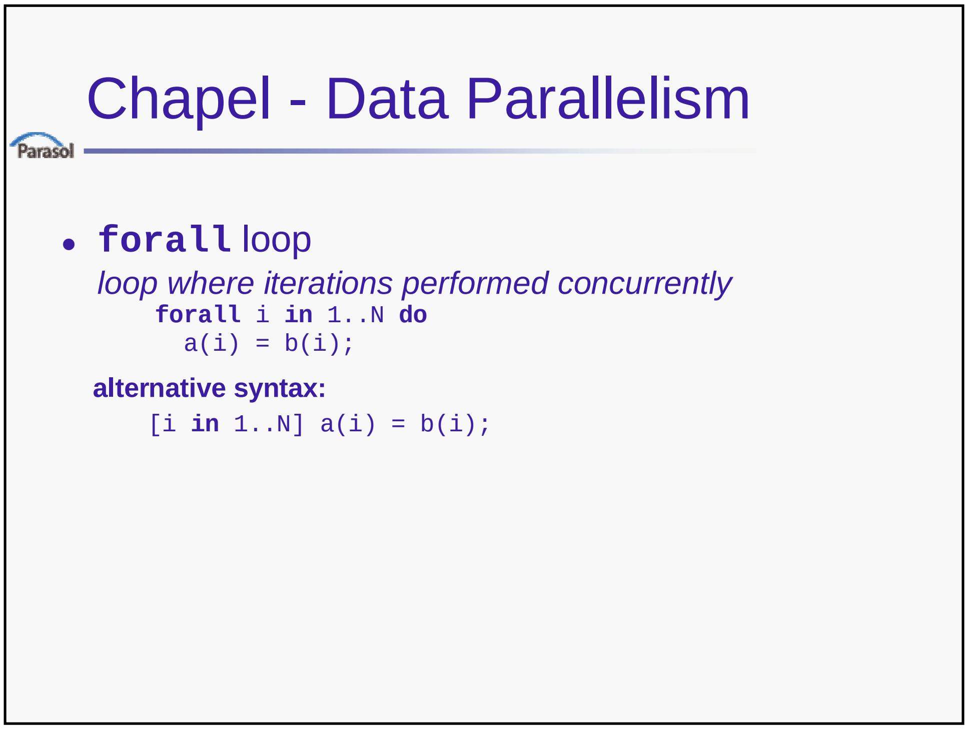
- The Cascade High-Productivity Language (Chapel)
  - Developed by Cray as part of DARPA HPCS program
  - Draws from HPF and ZPL
  - Designed for “general” parallelism
    Supports arbitrary nesting of task and data parallelism
  - Constructs for explicit data and work placement
  - OOP and generics support for code reuse

Adapted From:http://chapel.cs.washington.edu/ChapelForAHPCRC.pdf



The Chapel Model

- Execution Model
  - Explicit data parallelism with **`forall`**
  - Explicit task parallelism **`forall`**, **`cobegin`**, **`begin`**
  - Implicit communication
  - Synchronization
    - Implicit barrier after parallel constructs
    - Explicit constructs also included in language
  - Memory Consistency model still under development



Chapel - Data Parallelism

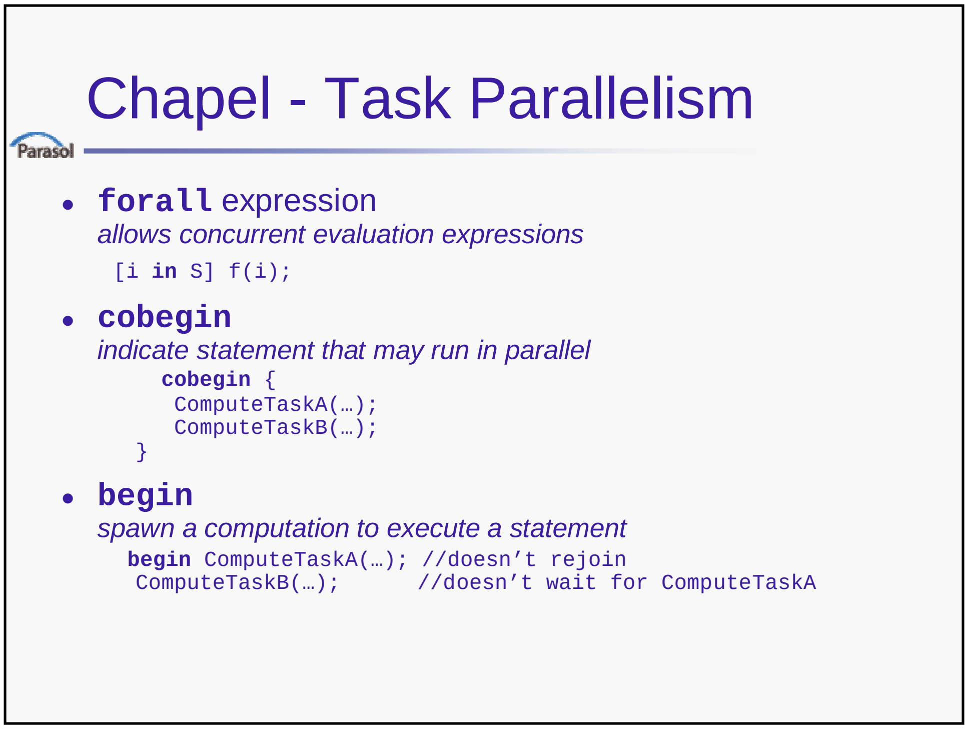
- **`forall`** loop

  loop where iterations performed concurrently

```
    forall i in 1..N do
      a(i) = b(i);
```

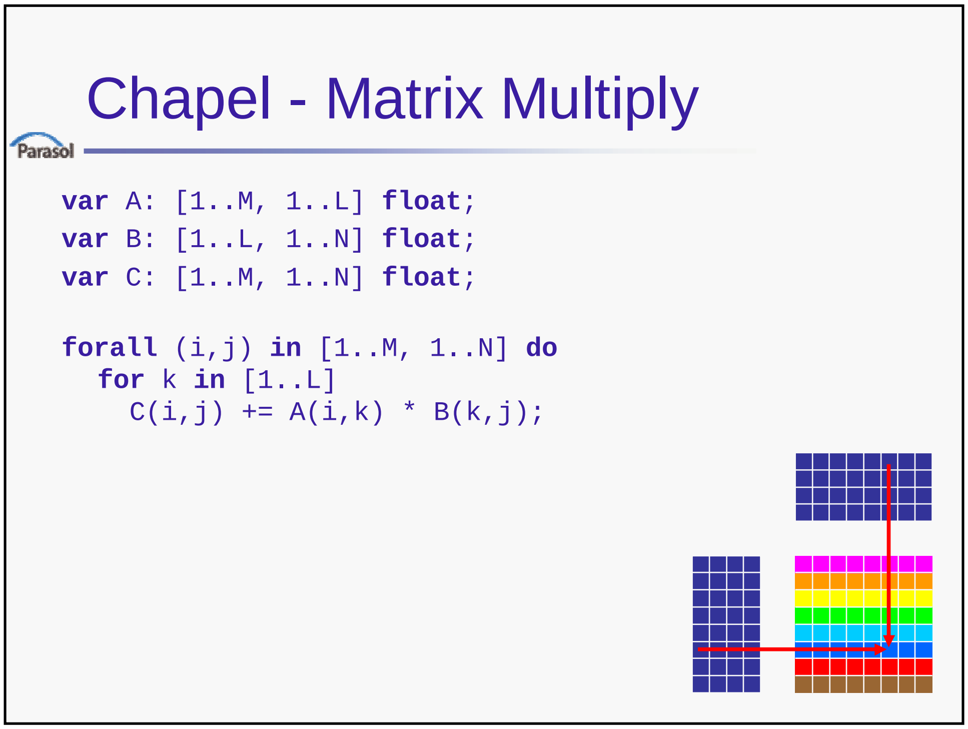
alternative syntax:

```
    [i in 1..N] a(i) = b(i);
```



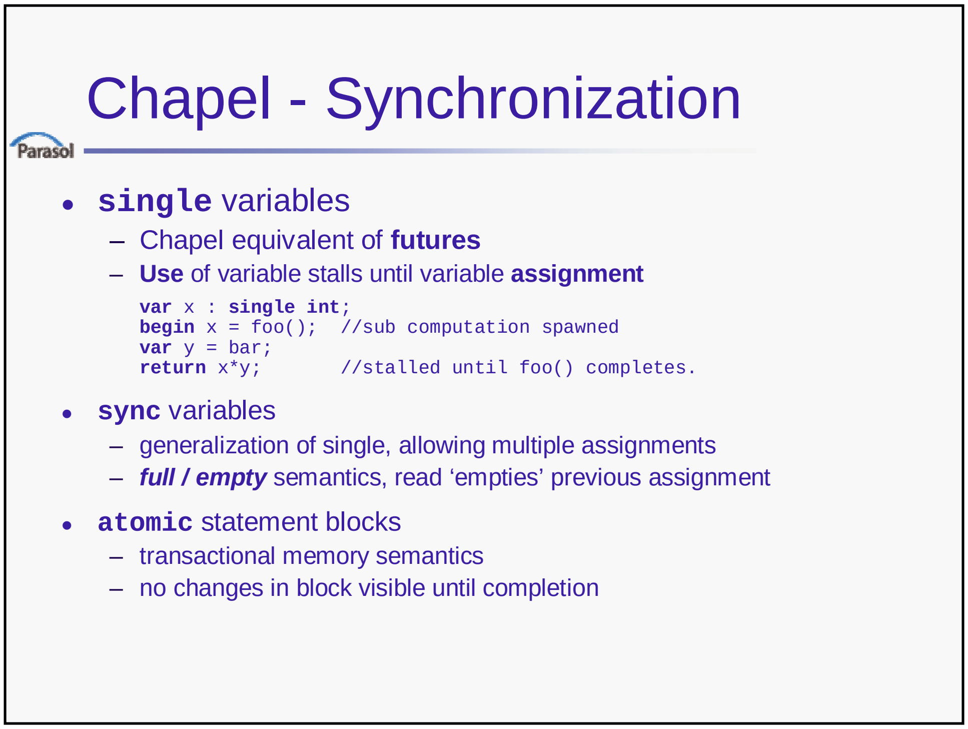
Chapel - Task Parallelism

- **`forall`** expression
  allows concurrent evaluation expressions
  ```
  [i in S] f(i);
  ```
- **`cobegin`**
  indicate statement that may run in parallel
  ```
      cobegin {
       ComputeTaskA(…);
       ComputeTaskB(…);
   }
  ```
- **`begin`**
  spawn a computation to execute a statement
  ```
  begin ComputeTaskA(…); //doesn’t rejoin
   ComputeTaskB(…);      //doesn’t wait for ComputeTaskA
  ```



Chapel - Matrix Multiply

```
var A: [1..M, 1..L] float;
var B: [1..L, 1..N] float;
var C: [1..M, 1..N] float;

forall (i,j) in [1..M, 1..N] do
  for k in [1..L]
    C(i,j) += A(i,k) * B(k,j);
```

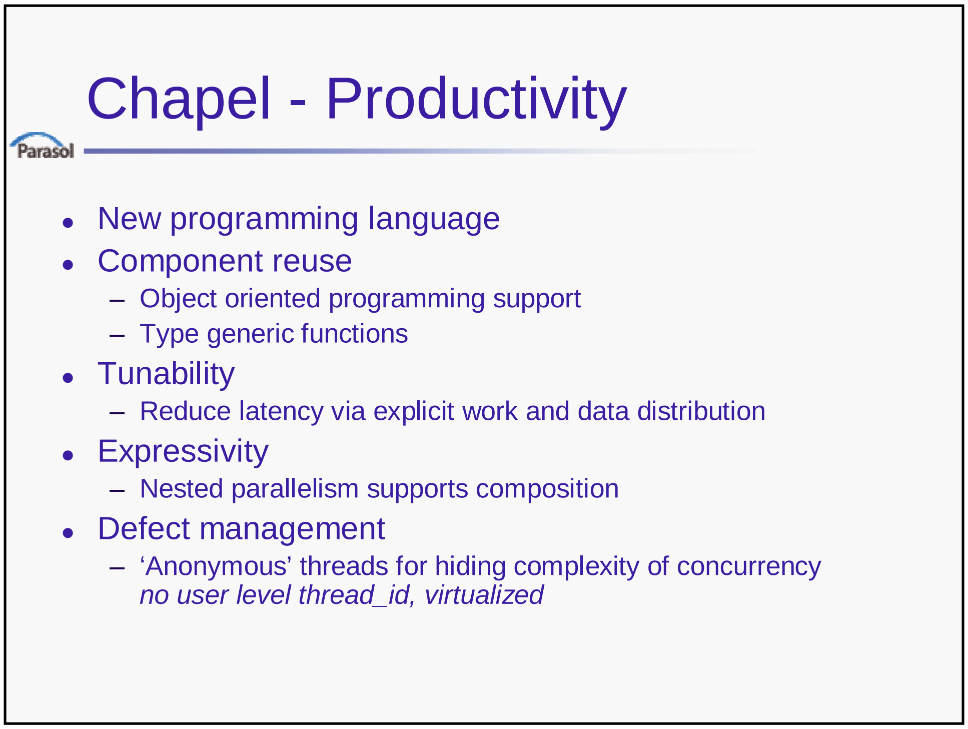


Chapel - Synchronization

- `single` variables
  - Chapel equivalent of **futures**
  - **Use** of variable stalls until variable **assignment**

```
var x : single int;
begin x = foo();  //sub computation spawned
var y = bar;
return x*y;       //stalled until foo() completes.
```

- **sync** variables
  - generalization of single, allowing multiple assignments
  - ***full / empty*** semantics, read ‘empties’ previous assignment
- **`atomic`** statement blocks
  - transactional memory semantics
  - no changes in block visible until completion



Chapel - Productivity

- New programming language
- Component reuse
  - Object oriented programming support
  - Type generic functions
- Tunability
  - Reduce latency via explicit work and data distribution
- Expressivity
  - Nested parallelism supports composition
- Defect management
  - ‘Anonymous’ threads for hiding complexity of concurrency
    no user level thread_id, virtualized

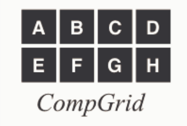
Chapel - Performance

- Latency Management
  - Reducing
    - Data placement - distributed domains
    - Work placement - **on** construct
  - Hiding
    - **`single`** variables
    - Runtime will employ multithreading, if available

Chapel - Latency Reduction

- Locales
  - Abstraction of processor or node
  - Basic component where memory accesses are assumed uniform
  - User interface defined in language
    - integer constant **numLocales**
    - type **`locale`** with (in)equality operator
    - array **`Locales`**`[1..`**`numLocales`**`]` of type **`locale`**

```
var CompGrid:[1..Rows, 1..Cols] local = ...;
```



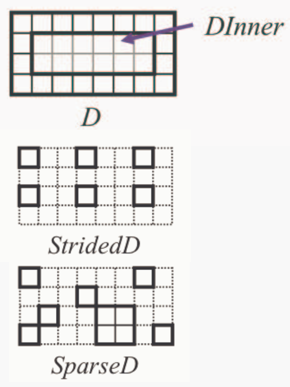
A	B	C	D
E	F	G	H

CompGrid

Chapel - Latency Reduction

- Domain
  - set of indices specifying size and shape of aggregate types (i.e., arrays, graphs, etc)

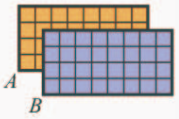
```
var m: integer = 4;
var n: integer = 8;
var D: domain(2) = [1..m, 1..n];
var DInner: domain(D) = [2..m-1, 2..n-1]


var StridedD: domain(D) = D by (2,3);


var indexList: seq(index(D)) = ...;
var SparseD: sparse domain(D) = indexList;
```



Chapel - Domains

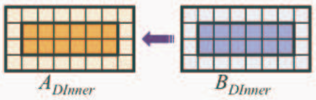
- Declaring arrays

  `var A, B: [D] float`



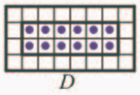
- Sub-array references

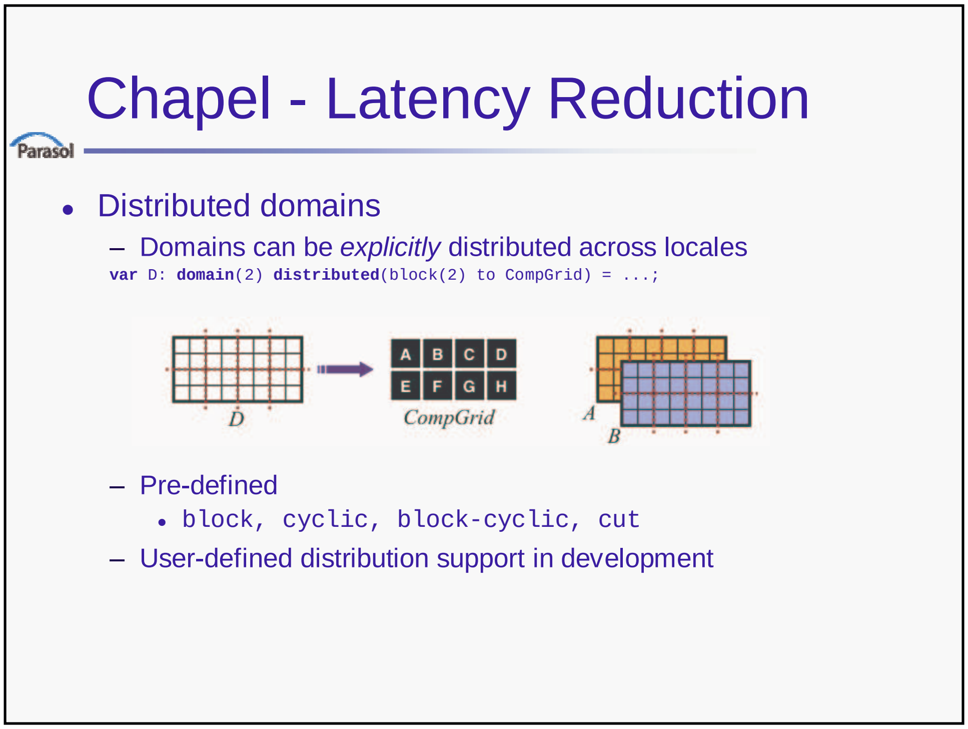
  `A(Dinner) = B(Dinner);`



- Parallel iteration

  `forall (i,j) in Dinner { A(i,j} = ...}`



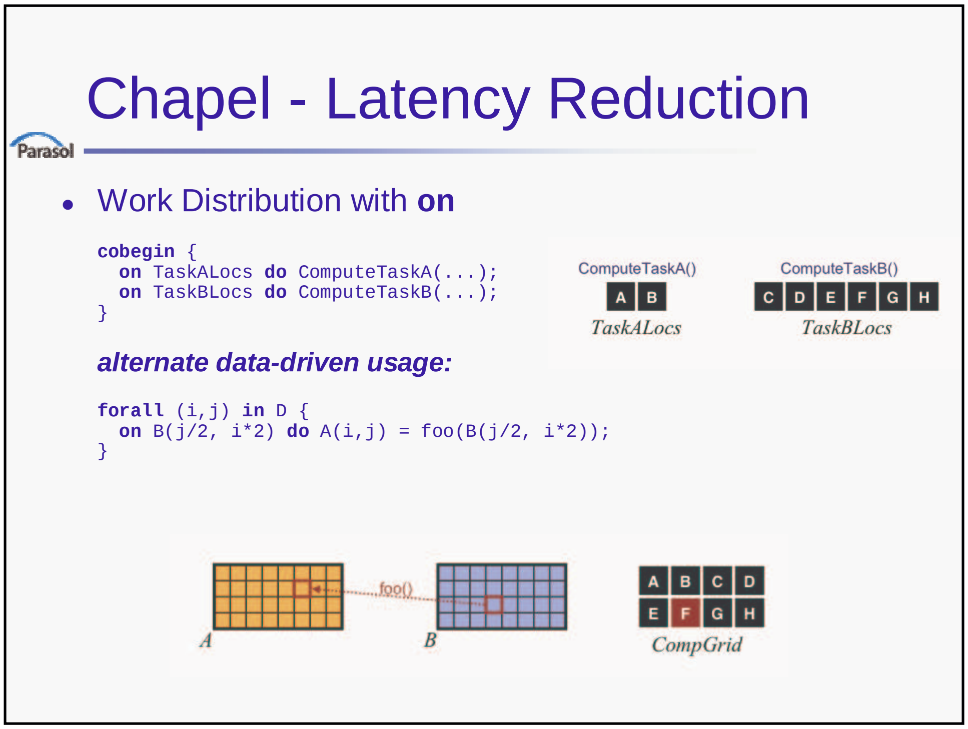


Chapel - Latency Reduction

- Distributed domains
  - Domains can be *explicitly* distributed across locales

```
var D: domain(2) distributed(block(2) to CompGrid) = ...;
```

  - Pre-defined
    - `block, cyclic, block-cyclic, cut`
  - User-defined distribution support in development



Chapel - Latency Reduction

- Work Distribution with **on**

```
cobegin {
  on TaskALocs do ComputeTaskA(...);
  on TaskBLocs do ComputeTaskB(...);
}
```

alternate data-driven usage:

```
forall (i,j) in D {
  on B(j/2, i*2) do A(i,j) = foo(B(j/2, i*2));
}
```

Chapel - Portability

- Language based solution, requires compiler
- Runtime system part of Chapel model. Responsible for mapping implicit multithreaded, high level code appropriately onto target architecture
- **locales** machine information available to programmer
- Parallel model not effected by underlying machine
- I/O API discussed in standard, scalability and implementation not discussed

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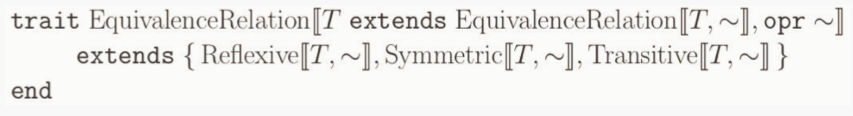
The Fortress Model

- Developed by Sun for DARPA HPCS program
- Draws from Java and functional languages
- Emphasis on growing language via strong library development support
- Places parallelism burden primarily on library developers
- Use of extended Unicode character set allow syntax to mimic mathematical formulas



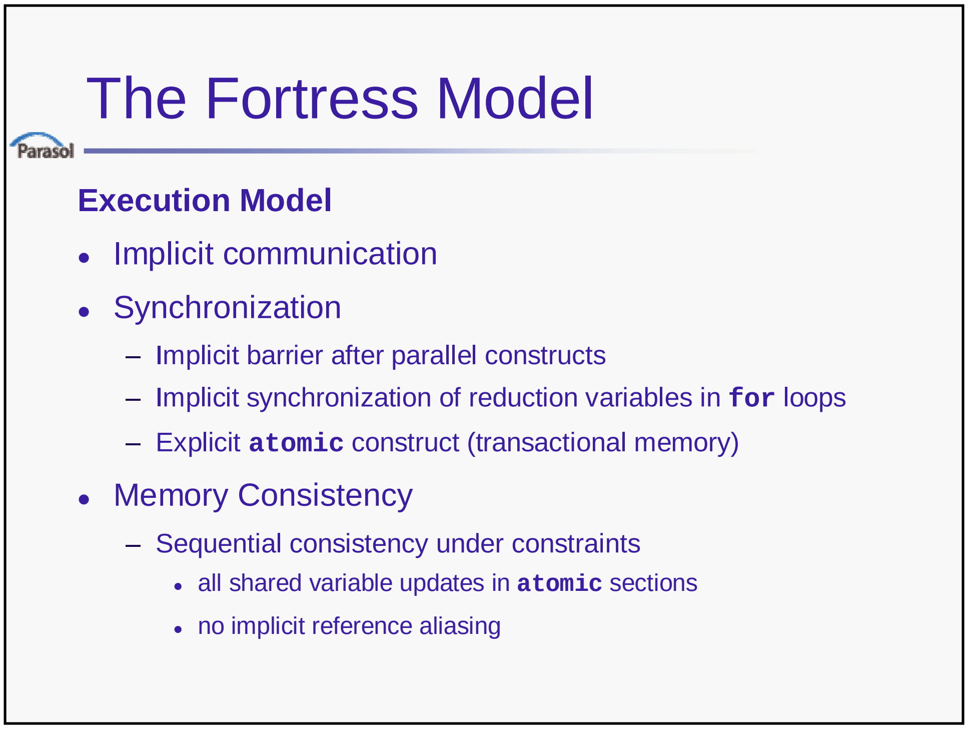
```
trait EquivalenceRelation⟦T extends EquivalenceRelation⟦T, ∼⟧, opr ∼⟧
      extends { Reflexive⟦T, ∼⟧, Symmetric⟦T, ∼⟧, Transitive⟦T, ∼⟧ }
end
```

Adapted From: http://irbseminars.intel-research.net/GuySteele.pdf

The Fortress Model

Execution Model

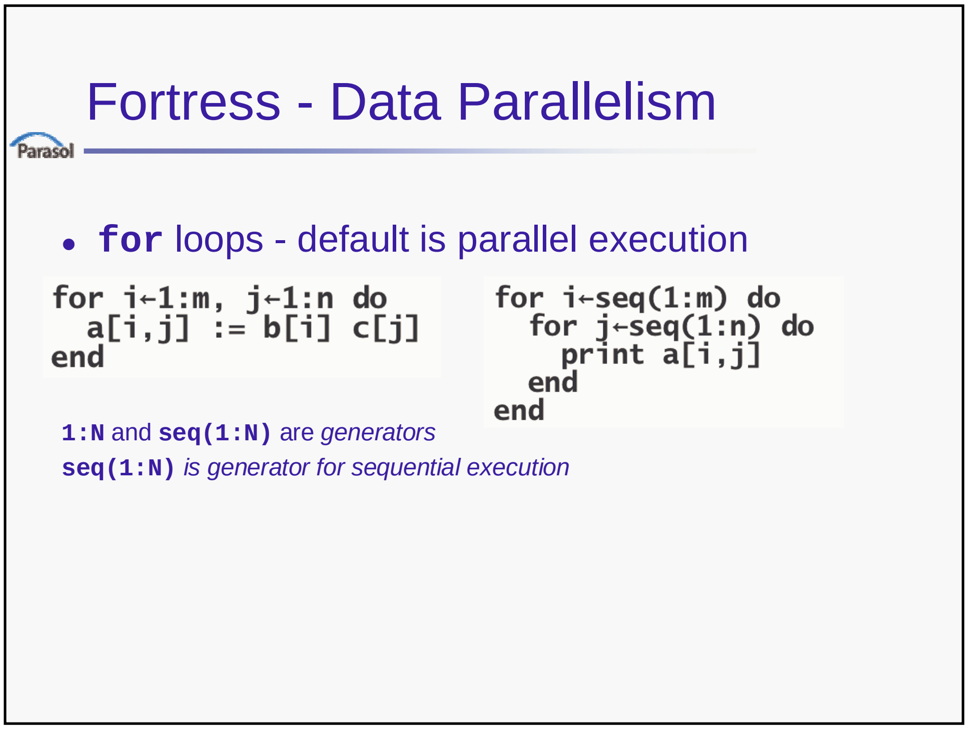
- User sees single-threaded execution by default
  - Loops are assumed parallel, unless otherwise specified
- Data parallelism
  - Implicit with **`for`** construct
  - Explicit ordering via custom Generators
- Explicit task parallelism
  - Tuple and **`do all`** constructs
  - Explicit with **`spawn`**



The Fortress Model

Execution Model

- Implicit communication
- Synchronization
  - Implicit barrier after parallel constructs
  - Implicit synchronization of reduction variables in **`for`** loops
  - Explicit **`atomic`** construct (transactional memory)
- Memory Consistency
  - Sequential consistency under constraints
    - all shared variable updates in **`atomic`** sections
    - no implicit reference aliasing



Fortress - Data Parallelism

- **`for`** loops - default is parallel execution

```
for i←1:m, j←1:n do
  a[i,j] := b[i] c[j]
end
```

```
for i←seq(1:m) do
  for j←seq(1:n) do
    print a[i,j]
  end
end
```

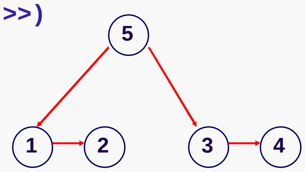
`1:N` and **`seq(1:N)`** are *generators*

`seq(1:N)` *is generator for sequential execution*

Fortress - Data Parallelism

- Generators
  - Controls parallelism in loops
  - Examples
    - Aggregates - **`<1,2,3,4>`**
    - Ranges - **`1:10`** and **`1:99:2`**
    - Index sets - **`a.indices`** and **`a.indices.rowMajor`**
    - **`seq(g)`** - sequential version of generator **`g`**
  - Can compose generators to order iterations

```
seq(<5,<seq(<1,2>), seq(<3,4>)>>)
```



Fortress - Explicit Task Parallelism

- Tuple expressions
  - comma separated exp. list executed concurrently

```
(foo(), bar())
```

- **`do-also`** blocks
  - all clauses executed concurrently

```
do
  foo()
also do
  bar()
end
```

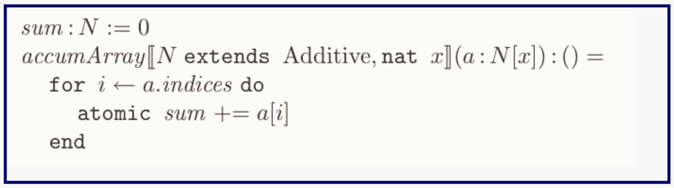
Fortress - Explicit Task Parallelism

- Spawn expressions (futures)

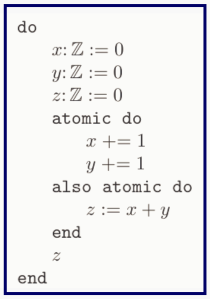
```
…
v = spawn do
  …
end
…
v.val()   //return value, block if not completed
v.ready() //return true iff v completed
v.wait()  //block if not completed, no return
value
v.stop()  //attempt to terminate thread
```

Fortress - Synchronization

- `atomic` blocks - transactional memory
  - other threads see block completed or not yet started
  - nested **`atomic`** and parallelism constructs allowed
  - **`tryatomic`** can detect conflicts or aborts



```
sum : N := 0
accumArray⟦N extends Additive, nat x⟧(a : N[x]) : () =
  for i ← a.indices do
    atomic sum += a[i]
  end
```



```
do
   x: ℤ := 0
   y: ℤ := 0
   z: ℤ := 0
   atomic do
      x += 1
      y += 1
   also atomic do
      z := x + y
   end
   z
end
```

Fortress - Productivity

- Defect management
  - Reduction
    - explicit parallelism and tuning primarily confined to libraries
  - Detection
    - integrated testing infrastructure
- Machine model
  - *Regions* give abstract machine topology

Fortress - Productivity

Expressivity

- High abstraction level
  - Source code closely matches formulas via extended Unicode charset
  - Types with checked physical units
  - Extensive operator overloading
- Composition and Reuse
  - Type-based generics
  - Arbitrary nested parallelism
  - Inheritance by traits
- Expandability
  - ‘Growable’ language philosophy aims to minimize core language constructs and maximize library implementations

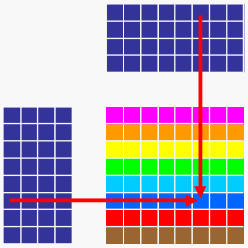
Fortress - Productivity

- Implementation refinement
  - Custom generators, distributions, and thread placement
- Defect management
  - Reduction
    - explicit parallelism and tuning primarily confined to libraries
  - Detection
    - integrated testing infrastructure
- Machine model
  - *Regions* give abstract machine topology

Fortress - Matrix Multiply

```
matmult(A: Matrix[/Float/],
        B: Matrix[/Float/])
        : Matrix[/Float/]
  A B
end

C = matmult(A,B)
```

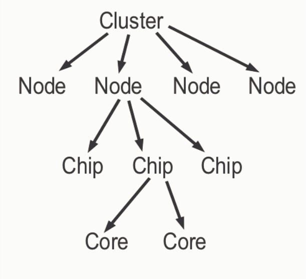


Fortress - Performance

- Regions for describing system topology
- Work placement with **`at`**
- Data placement with Distributions
- **`spawn`** expression to hide latency

Fortress - Regions

- Tree structure of CPUs and memory resources
  - Allocation heaps
  - Parallelism
  - Memory coherence
- Every thread, object, and array element has associated region

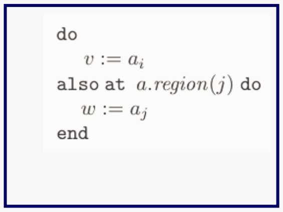


```
obj.region()   //region where object obj is located
r.isLocalTo(s) //is region r in region tree rooted at s
```

Fortress - Latency Reduction

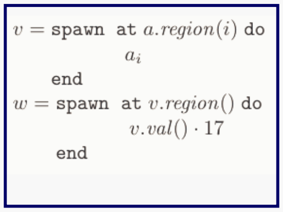
- Explicit work placement with **`at`**

inside do `also`



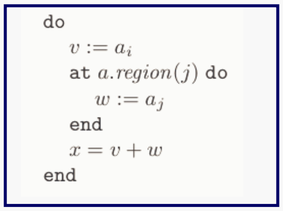
```
do
    $v := a_i$
also at $a.region(j)$ do
    $w := a_j$
end
```

with spawn



```
$v =$ spawn at $a.region(i)$ do
            $a_i$
    end
$w =$ spawn at $v.region()$ do
            $v.val() \cdot 17$
    end
```

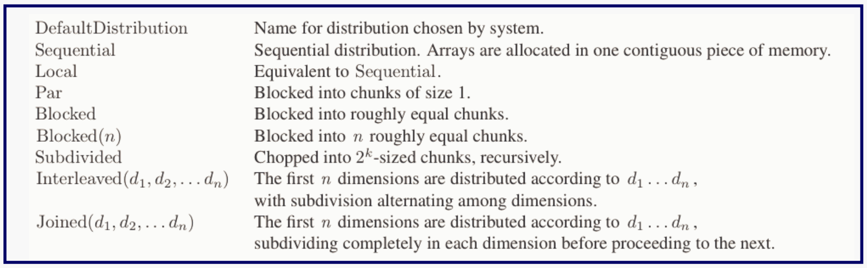
regular block stmt



```
do
    $v := a_i$
    at $a.region(j)$ do
        $w := a_j$
    end
    $x = v + w$
end
```

Fortress - Latency Reduction

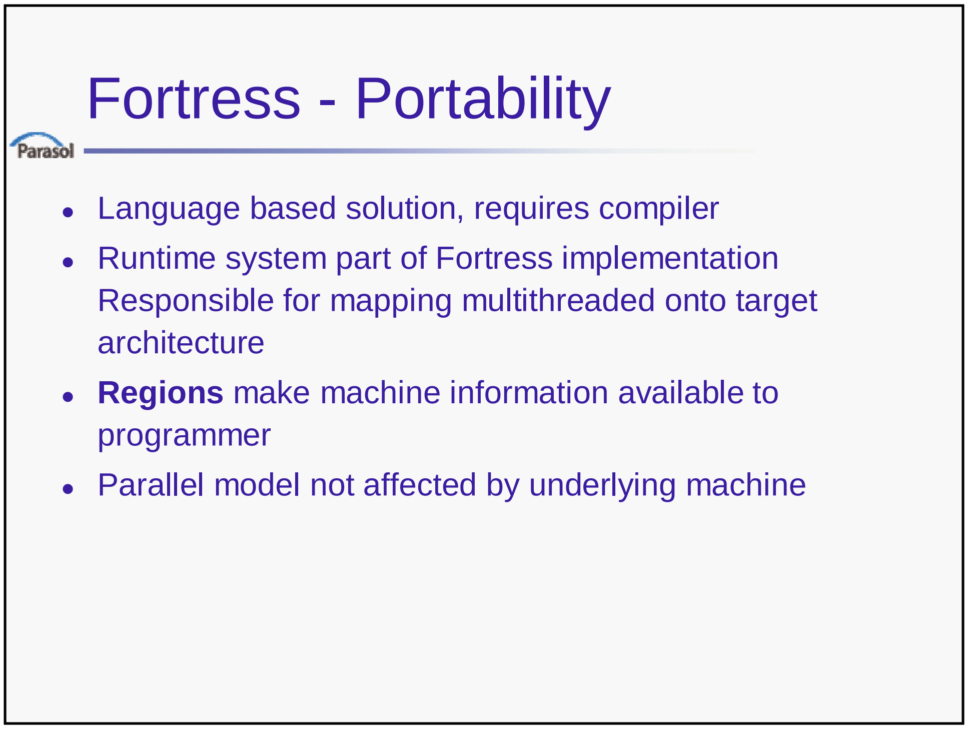
- Explicit data placement with Distributions



DefaultDistribution	Name for distribution chosen by system.
Sequential	Sequential distribution. Arrays are allocated in one contiguous piece of memory.
Local	Equivalent to Sequential.
Par	Blocked into chunks of size 1.
Blocked	Blocked into roughly equal chunks.
Blocked(n)	Blocked into n roughly equal chunks.
Subdivided	Chopped into 2^k-sized chunks, recursively.
Interleaved$(d_1, d_2, \ldots d_n)$	The first n dimensions are distributed according to $d_1 \ldots d_n$, with subdivision alternating among dimensions.
Joined$(d_1, d_2, \ldots d_n)$	The first n dimensions are distributed according to $d_1 \ldots d_n$, subdividing completely in each dimension before proceeding to the next.

```
a = Blocked.array(n,n,1); //Pencils along z axis
```

- User can define custom distribution by inheriting **Distribution** trait
  - Standard distributions implemented in this manner



Fortress - Portability

- Language based solution, requires compiler
- Runtime system part of Fortress implementation Responsible for mapping multithreaded onto target architecture
- **Regions** make machine information available to programmer
- Parallel model not affected by underlying machine

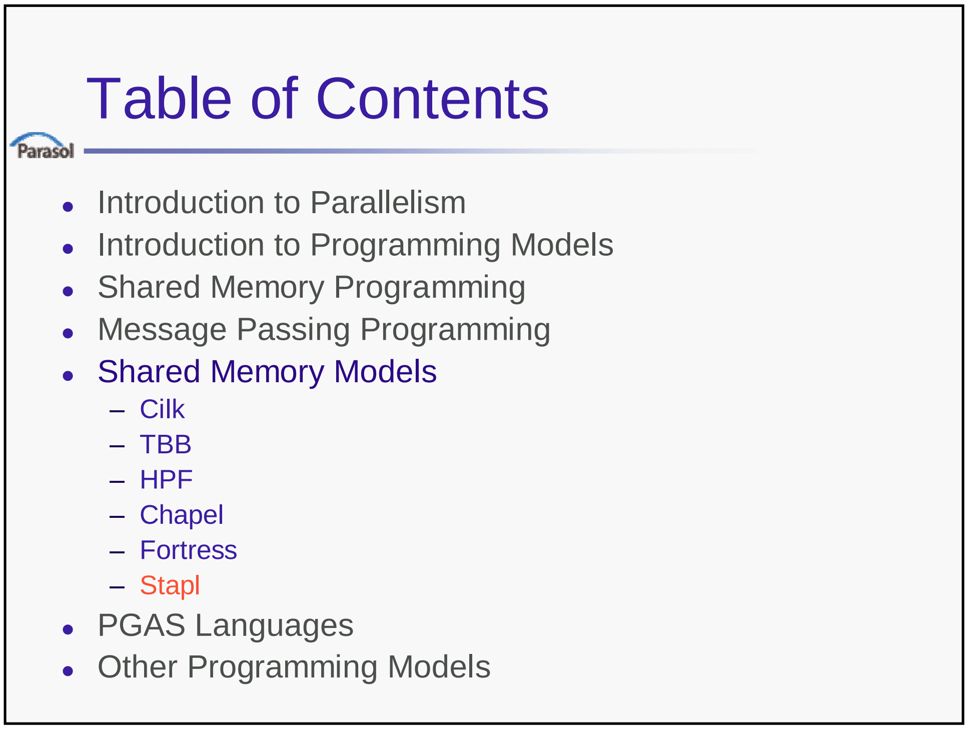


Table of Contents

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- Shared Memory Models
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  - TBB
  - HPF
  - Chapel
  - Fortress
  - Stapl
- PGAS Languages
- Other Programming Models

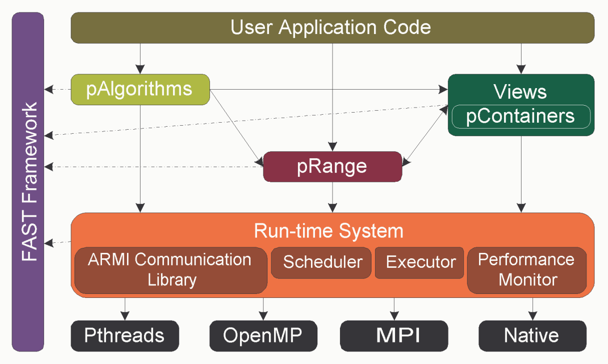
The STAPL Model

- Standard Adaptive Parallel Library
- Developed by Lawrence Rauchwerger, Nancy Amato, Bjarne Stroustrup and several grad students at Texas A&M
- Library similar and compatible with to STL
- Strong library development support
- Places parallelism burden primarily on library developers
- Commercial simple variant : Intel TBB

Adapted From: http://irbseminars.intel-research.net/GuySteele.pdf

Standard Template Adaptive Parallel Library

A library of parallel, generic constructs based on the C++ Standard Template Library (STL).



User Application Code

pAlgorithms

Views

pContainers

pRange

FAST Framework

Run-time System

ARMI Communication Library

Scheduler

Executor

Performance Monitor

Pthreads

OpenMP

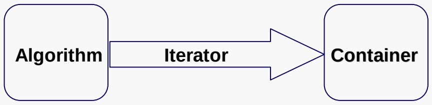
MPI

Native

Standard Template Library (STL)

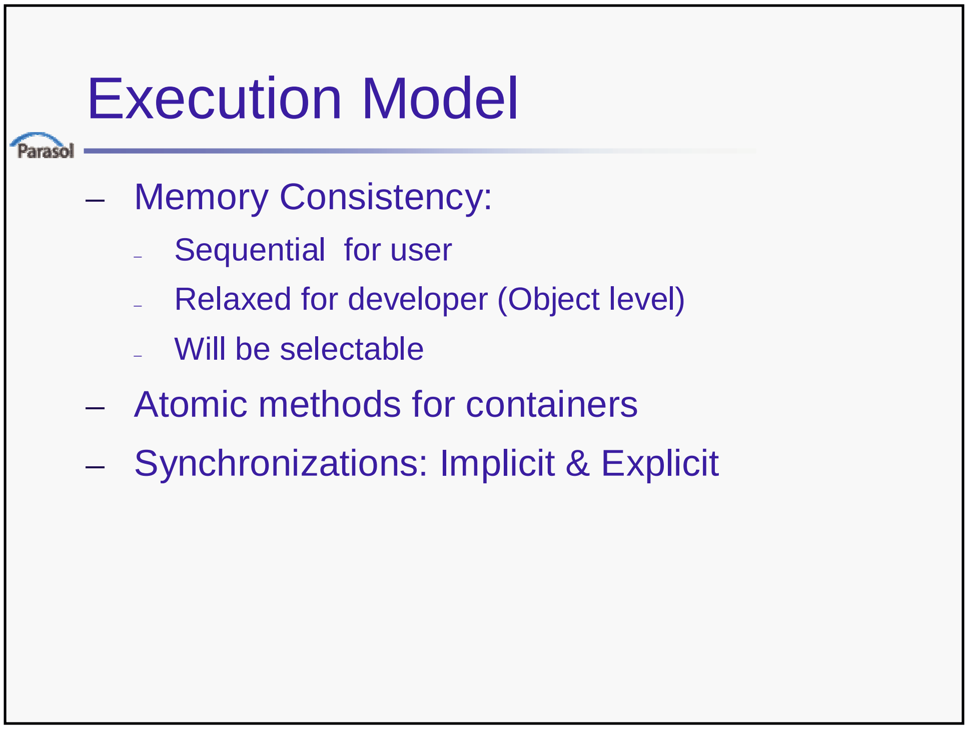
Generic programming components using C++ templates.

- **Containers - collection of other objects.**
  - vector, list, deque, set, multiset, map, multi_map, hash_map.
  - Templated by data type. vector<int> v(50);
- **Algorithms - manipulate the data stored in containers.**
  - manipulate the data stored in containers.
  - count(), reverse(), sort(), accumulate(), for_each(), reverse().
- **Iterators - Decouple algorithms from containers.**
  - Provide generic ***element access*** to data in containers.
  - can define custom ***traversal*** of container (e.g., every other element)
  - count(vector.begin(), vector.end(), 18);



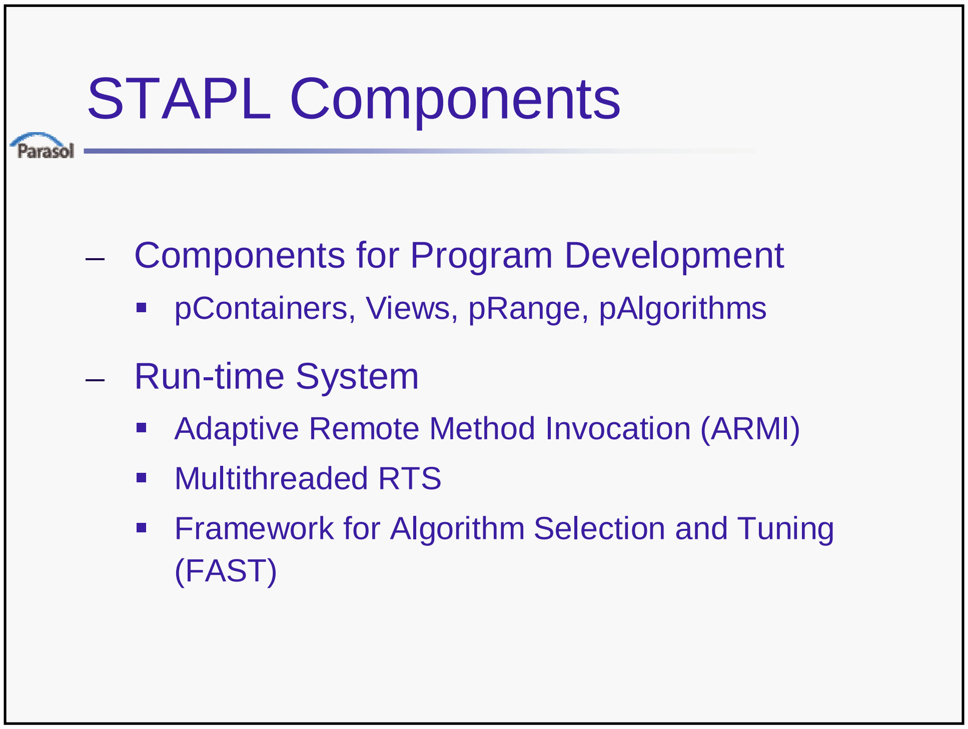
Execution Model

- Two models: User and Library Developer
- Single threaded – User
- Multithreaded – Developer
- Shared memory – User
- PGAS – Developer
- Data & task parallelism
- Implicit communications: User
- Explicit communications: Developer



Execution Model

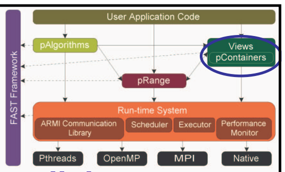
- Memory Consistency:
  - Sequential for user
  - Relaxed for developer (Object level)
  - Will be selectable
- Atomic methods for containers
- Synchronizations: Implicit & Explicit



STAPL Components

- Components for Program Development
  - pContainers, Views, pRange, pAlgorithms
- Run-time System
  - Adaptive Remote Method Invocation (ARMI)
  - Multithreaded RTS
  - Framework for Algorithm Selection and Tuning (FAST)

pContainers



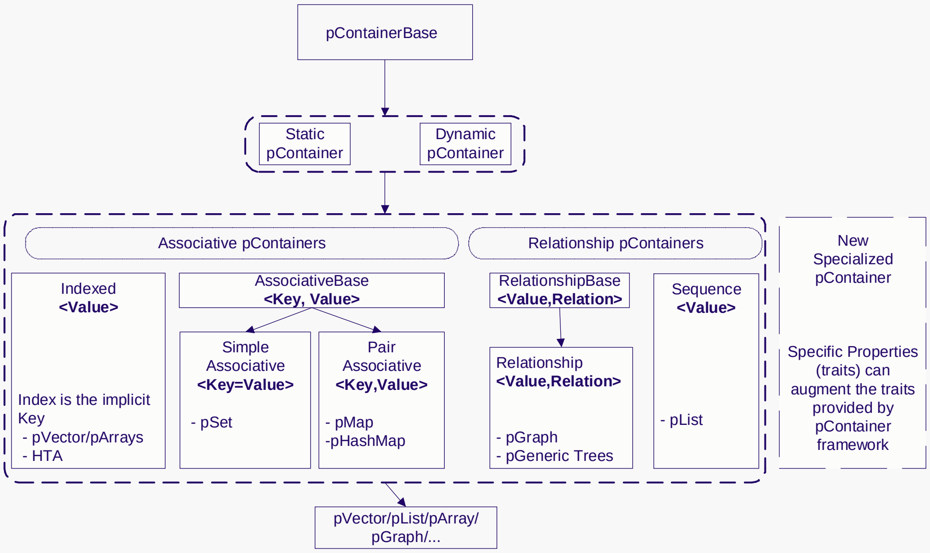
Generic, distributed data structures with parallel methods.

- Ease of Use
  - Shared object view
  - Generic access mechanism through Views
  - Handles data distribution and remote data access internally
  - Interface equivalent with sequential counterpart
- Efficiency
  - OO design to optimize specific containers
  - Template parameters allow further customization
- Extendability
  - New pContainters extend Base classes
- Composability
  - pContainers of pContainers

Currently Implemented

pArray, pVector, pGraph, pMap, pHashMap, pSet, pList

pContainer Taxonomy

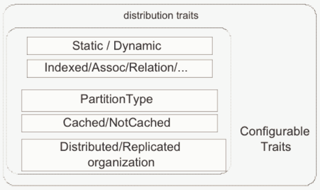

pContainerBase
Static pContainer
Dynamic pContainer
Associative pContainers
Relationship pContainers
Indexed **<Value>**
Index is the implicit Key
- pVector/pArrays
- HTA
AssociativeBase **<Key, Value>**
Simple Associative **<Key=Value>**
- pSet
Pair Associative **<Key,Value>**
- pMap
-pHashMap
RelationshipBase **<Value,Relation>**
Relationship **<Value,Relation>**
- pGraph
- pGeneric Trees
Sequence **<Value>**
- pList
New Specialized pContainer
Specific Properties (traits) can augment the traits provided by pContainer framework
pVector/pList/pArray/ pGraph/...

pContainer Customization

Optional user customization through pContainer **Traits**.

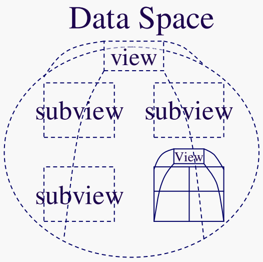
- Enable/Disable Performance Monitoring.
- Select Partition Strategies.
- Enable/Disable Thread Safety.
- Select Consistency Models

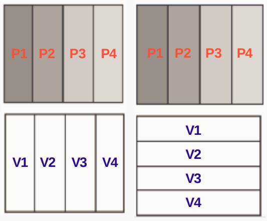
```
class p_array_traits {
 Indexed, Assoc/Key=Index,
 Static,IndexedView<Static,..., Random>,
 DistributionManagerTraits,
 -u-Monitoring,
 -u-Relaxed
}
```



View

- STAPL equivalent of STL iterator, extended to allow for efficient parallelism.
- Focus on processing value range, instead of single item.
- Generic *access* mechanism to pContainer.
- Custom *traversal* of pContainer elements.
- Hierarchically defined to allow control of locality and granularity of communication/computation.

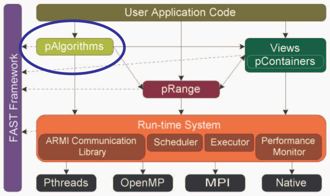




Gray -> the pContainer physical partition.

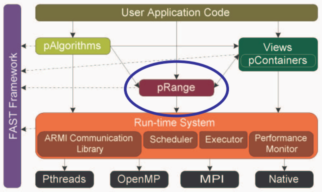
Transparent -> logical views of the data.

pAlgorithms

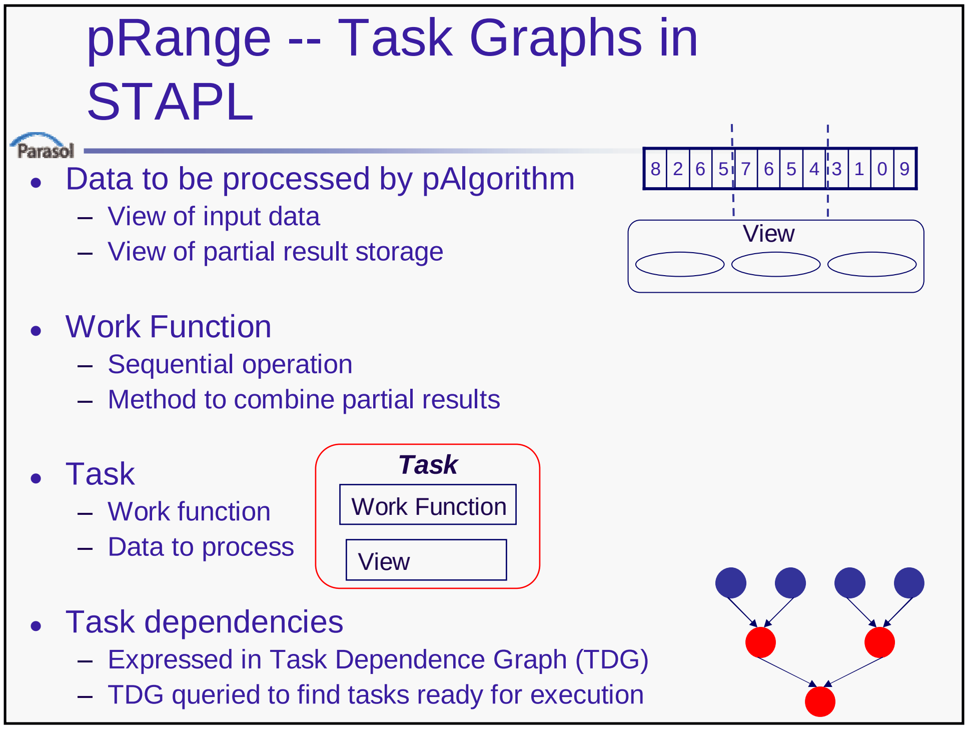


- pAlgorithms in STAPL
  - Parallel counterparts of STL algorithms provided in STAPL.
  - Common parallel algorithms.
    - Prefix sums
    - List ranking
  - pContainer specific algorithms.
    - Strongly Connected Components (pGraph)
    - Euler Tour (pGraph)
    - Matrix multiplication (pMatrix)
  - Often, multiple implementations exist that are adaptively used by the library.

pRange



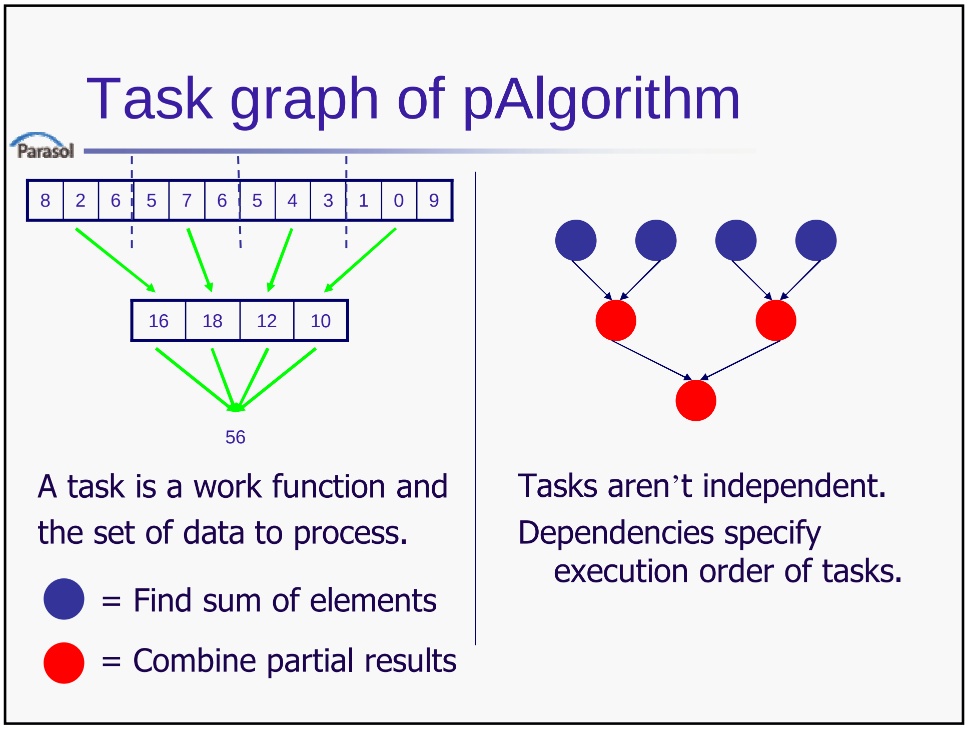
- pRange is a parallel task graph.
- Unifies work and data parallelism.
- Recursively defined as a tree of *subranges.*



pRange -- Task Graphs in STAPL

- Data to be processed by pAlgorithm
  - View of input data
  - View of partial result storage
- Work Function
  - Sequential operation
  - Method to combine partial results
- Task
  - Work function
  - Data to process
- Task dependencies
  - Expressed in Task Dependence Graph (TDG)
  - TDG queried to find tasks ready for execution

8 2 6 5 7 6 5 4 3 1 0 9
View
Task
Work Function
View



Task graph of pAlgorithm

A task is a work function and the set of data to process.

● = Find sum of elements

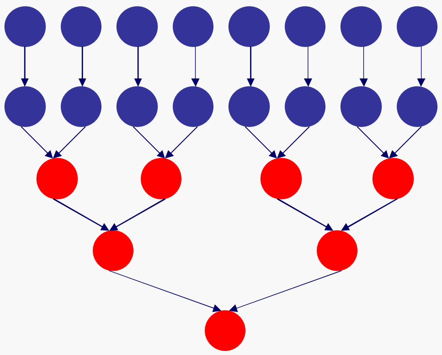
● = Combine partial results

Tasks aren't independent.

Dependencies specify execution order of tasks.

Composing Task Graphs

- Increases amount of concurrent work available
- Forms a MIMD computation
- Dependencies between tasks specified during composition



● = Add 7 to each element

● = Find sum of elements

🔴 = Combine partial results

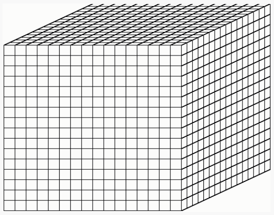
Dependencies only needed if tasks process the same data

Simple Dependence Specification

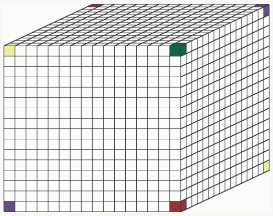
- Goal: Developer concisely expresses dependencies
  - Enumeration of dependencies is unmanageable
- Common patterns will be supported in pRange
  - Sequential – sources depend on sinks
  - Independent – no new dependencies needed in composed graph
  - Pipelined – dependencies follow a regular pattern

Discrete Ordinates Particle Transport Computation

- Important application for DOE
  - E.g., Sweep3D and UMT2K
- Large, on-going DOE project at TAMU to develop application in STAPL (TAXI)

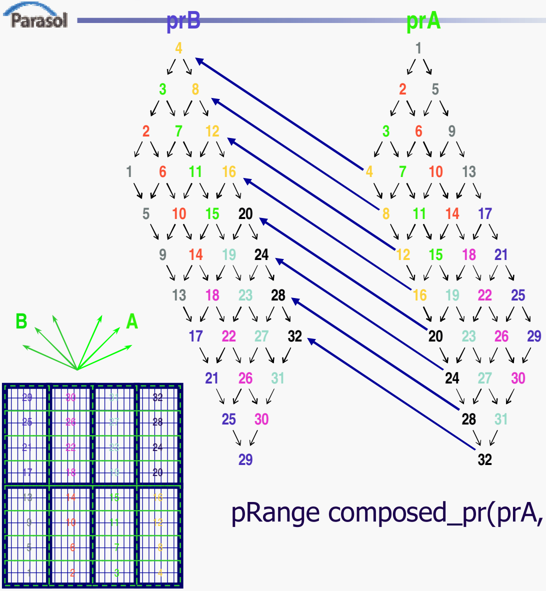


One sweep



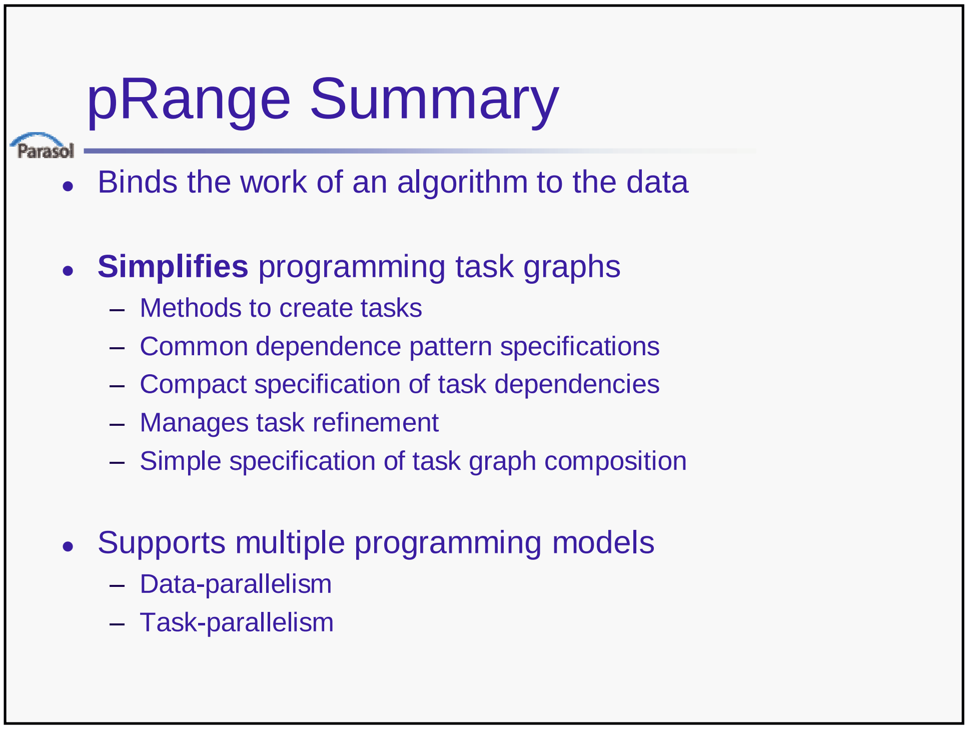
Eight simultaneous sweeps

Pipeline Pattern Example



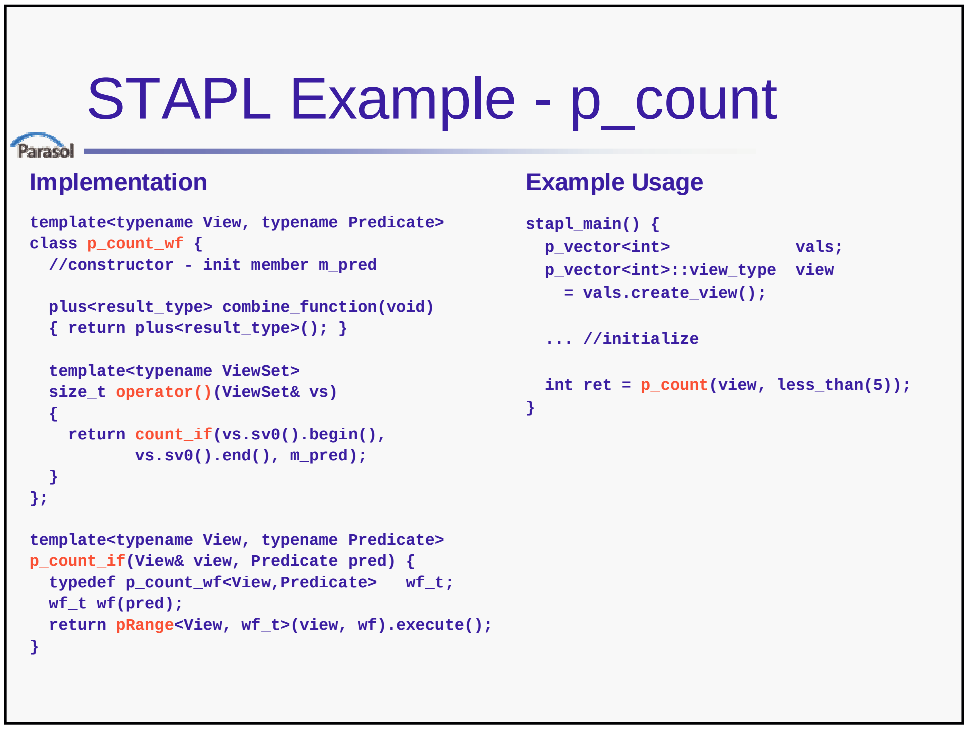
- pRanges are sweeps in particle transport application
- Reflective materials on problem boundary create dependencies
- Pipeline pattern will allow easy composition

pRange composed_pr(prA, prB, Pipeline(4,32,4));



pRange Summary

- Binds the work of an algorithm to the data
- **Simplifies** programming task graphs
  - Methods to create tasks
  - Common dependence pattern specifications
  - Compact specification of task dependencies
  - Manages task refinement
  - Simple specification of task graph composition
- Supports multiple programming models
  - Data-parallelism
  - Task-parallelism



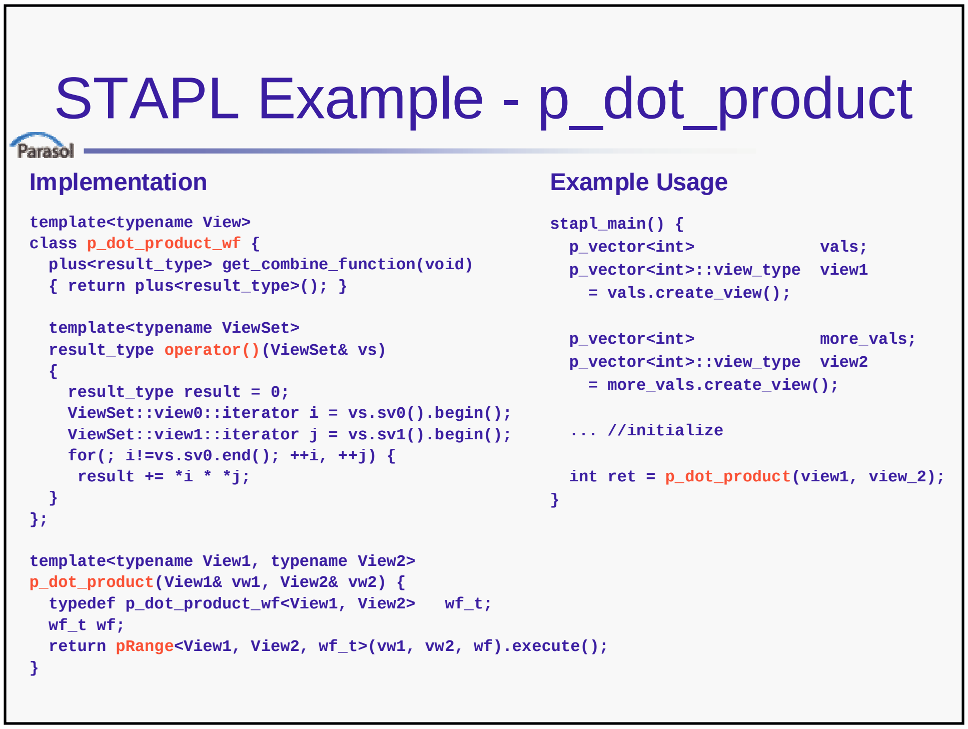
STAPL Example - p_count

Implementation

```
template<typename View, typename Predicate>
class p_count_wf {
  //constructor - init member m_pred

  plus<result_type> combine_function(void)
  { return plus<result_type>(); }

  template<typename ViewSet>
  size_t operator()(ViewSet& vs)
  {
    return count_if(vs.sv0().begin(),
           vs.sv0().end(), m_pred);
  }
};

template<typename View, typename Predicate>
p_count_if(View& view, Predicate pred) {
  typedef p_count_wf<View,Predicate>   wf_t;
  wf_t wf(pred);
  return pRange<View, wf_t>(view, wf).execute();
}
```

Example Usage

```
stapl_main() {
  p_vector<int>             vals;
  p_vector<int>::view_type  view
    = vals.create_view();

  ... //initialize

  int ret = p_count(view, less_than(5));
}
```



STAPL Example - p_dot_product

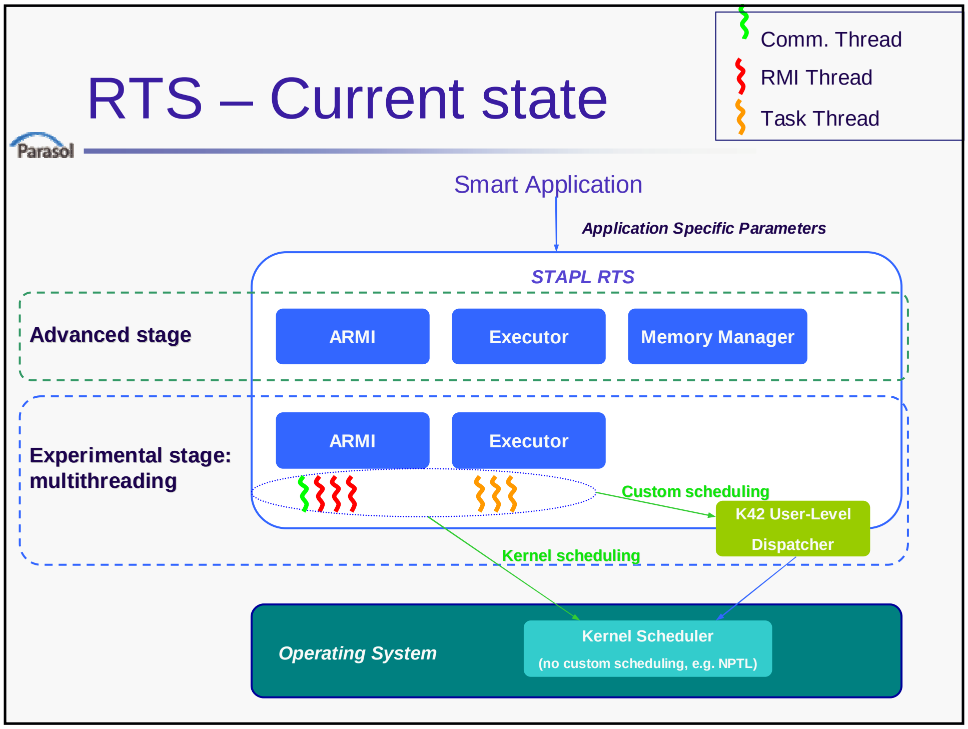
Parasol

Implementation

```
template<typename View>
class p_dot_product_wf {
  plus<result_type> get_combine_function(void)
  { return plus<result_type>(); }

  template<typename ViewSet>
  result_type operator()(ViewSet& vs)
  {
    result_type result = 0;
    ViewSet::view0::iterator i = vs.sv0().begin();
    ViewSet::view1::iterator j = vs.sv1().begin();
    for(; i!=vs.sv0.end(); ++i, ++j) {
     result += *i * *j;
  }
};

template<typename View1, typename View2>
p_dot_product(View1& vw1, View2& vw2) {
  typedef p_dot_product_wf<View1, View2>   wf_t;
  wf_t wf;
  return pRange<View1, View2, wf_t>(vw1, vw2, wf).execute();
}
```

Example Usage

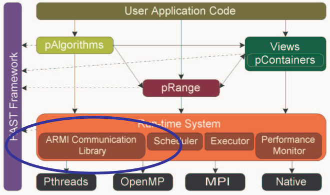
```
stapl_main() {
  p_vector<int>              vals;
  p_vector<int>::view_type  view1
    = vals.create_view();

  p_vector<int>              more_vals;
  p_vector<int>::view_type  view2
    = more_vals.create_view();

  ... //initialize

  int ret = p_dot_product(view1, view_2);
}
```



RTS – Current state

Parasol

ARMI – Current State



ARMI: Adaptive Remote Method Invocation

- Abstraction of shared-memory and message passing communication layer (MPI, pThreads, OpenMP, mixed, Converse).
- Programmer expresses fine-grain parallelism that ARMI adaptively coarsens to balance latency versus overhead.
- Support for sync, async, point-to-point and group communication.
- Automated (de)serialization of C++ classes.

ARMI can be as easy/natural as shared memory and as efficient as message passing.

ARMI Communication Primitives

Point to Point Communication

armi_async - non-blocking: doesn't wait for request arrival or completion.

armi_sync - blocking and non-blocking versions.

Collective Operations

armi_broadcast, armi_reduce, etc.

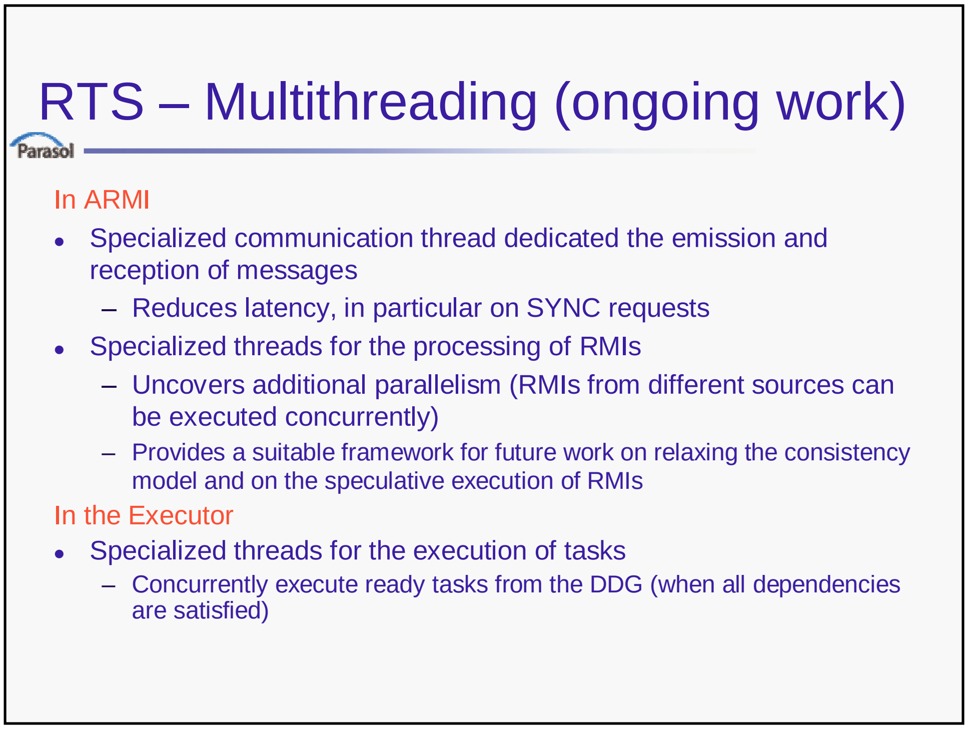
can adaptively set groups for communication.

Synchronization

armi_fence, armi_barrier - fence implements distributed termination algorithm to ensure that all requests sent, received, and serviced.

armi_wait - blocks until at least at least one request is received and serviced.

armi_flush - empties local send buffer, pushing outstanding to remote destinations.



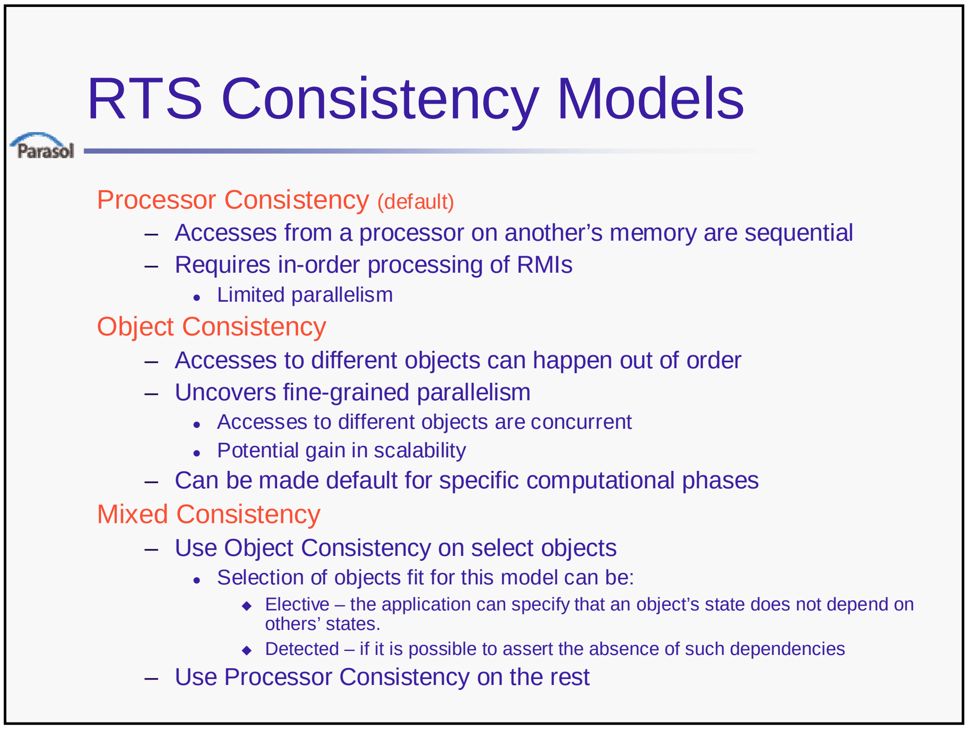
RTS – Multithreading (ongoing work)

In ARMI

- Specialized communication thread dedicated the emission and reception of messages
  - Reduces latency, in particular on SYNC requests
- Specialized threads for the processing of RMIs
  - Uncovers additional parallelism (RMIs from different sources can be executed concurrently)
  - Provides a suitable framework for future work on relaxing the consistency model and on the speculative execution of RMIs

In the Executor

- Specialized threads for the execution of tasks
  - Concurrently execute ready tasks from the DDG (when all dependencies are satisfied)



RTS Consistency Models

Processor Consistency (default)

- Accesses from a processor on another's memory are sequential
- Requires in-order processing of RMIs
  - Limited parallelism

Object Consistency

- Accesses to different objects can happen out of order
- Uncovers fine-grained parallelism
  - Accesses to different objects are concurrent
  - Potential gain in scalability
- Can be made default for specific computational phases

Mixed Consistency

- Use Object Consistency on select objects
  - Selection of objects fit for this model can be:
    - Elective – the application can specify that an object's state does not depend on others' states.
    - Detected – if it is possible to assert the absence of such dependencies
- Use Processor Consistency on the rest

RTS Executor

Customized task scheduling

- Executor maintains a ready queue (all tasks for which dependencies are satisfied in the DDG)
- Order tasks from the ready queue based on a scheduling policy (e.g. round robin, static block or interleaved block scheduling, dynamic scheduling …)
- The RTS decides the policy, but the user can also specify it himself
- Policies can differ for every pRange

Customized load balancing

- Implement load balancing strategies (e.g. work stealing)
- Allow the user to choose the strategy
- K42 : generate a customized work migration manager

RTS Synchronization

- Efficient implementation of synchronization primitives is crucial
  - One of the main performance bottlenecks in parallel computing
  - Common scalability limitation

Fence

- Efficient implementation using a novel Distributed Termination Detection algorithm

Global Distributed Locks

- Symmetrical implementation to avoid contention
- Support for logically recursive locks (required by the compositional SmartApps framework)

Group-based synchronization

- Allows efficient usage of ad-hoc computation groups
- Semantic equivalent of the global primitives
- Scalability requirement for large-scale systems

Productivity

- Implicit parallelism
- Implicit synchronizations/communications
- Composable (closed under composition)
- Reusable (library)
- Tunable by experts (library not language)
- Compiles with any C++ compiler (GCC)
- Optionally exposes machine info.
- Shared Memory view for user
- High level of abstraction – Generic Programming

Performance

- Latency reduction: Locales , data distribution
- Latency Hiding: RMI, multithreading, Asynch Communications
- Optionally exposes machine info.
- Manually tunable for experts
- Adaptivity to input and machine (machine learning)

Portability

- Library – no need for special compiler
- RTS needs to be ported – not much else
- High level of abstraction

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http://supertech.csail.mit.edu/cilk/manual-5.4.3.pdf

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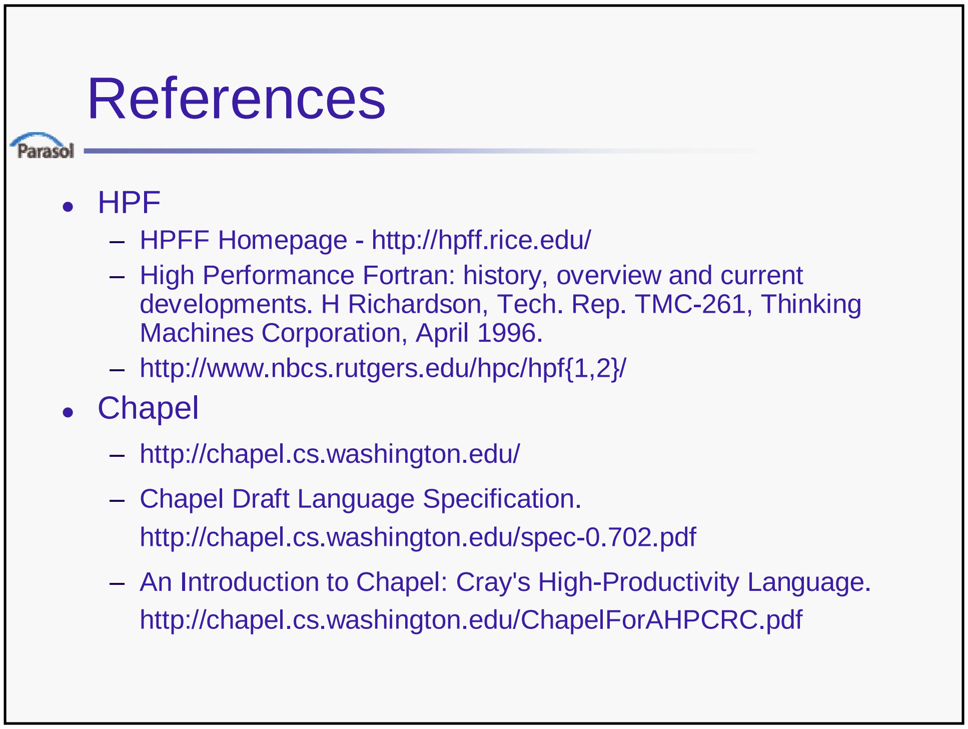
TBB

http://www.intel.com/cd/software/products/asmo-na/eng/294797.htm

TBB Reference Manual – provided with package

http://idfemea.intel.com/2006/prague/download/SShah_IDF_Keynote_2006-10-03_v1.pdf



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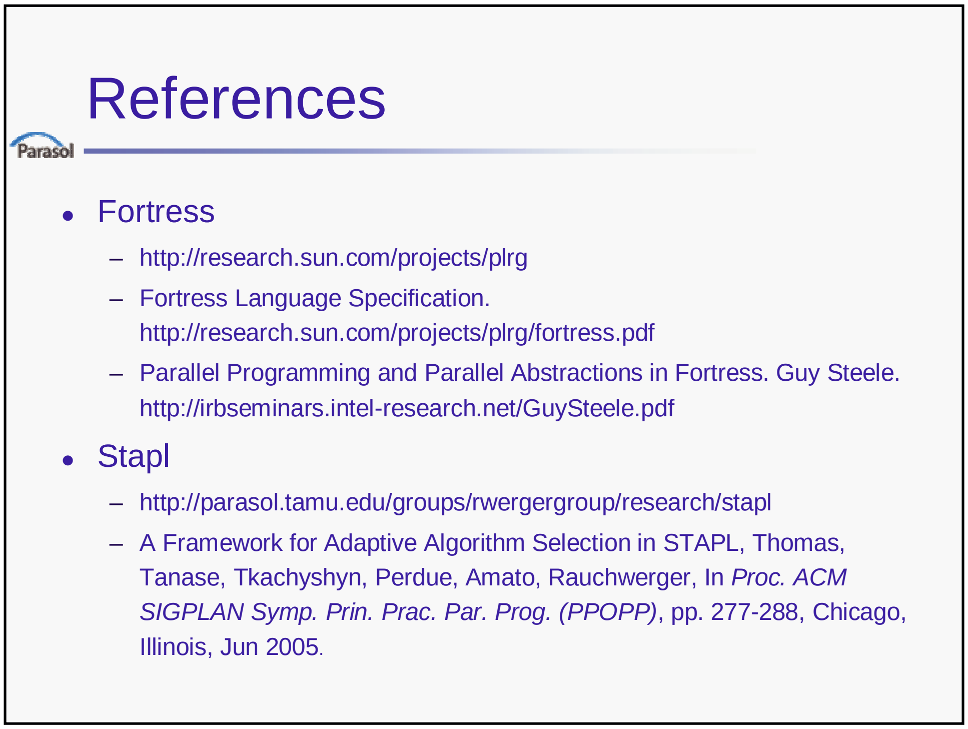

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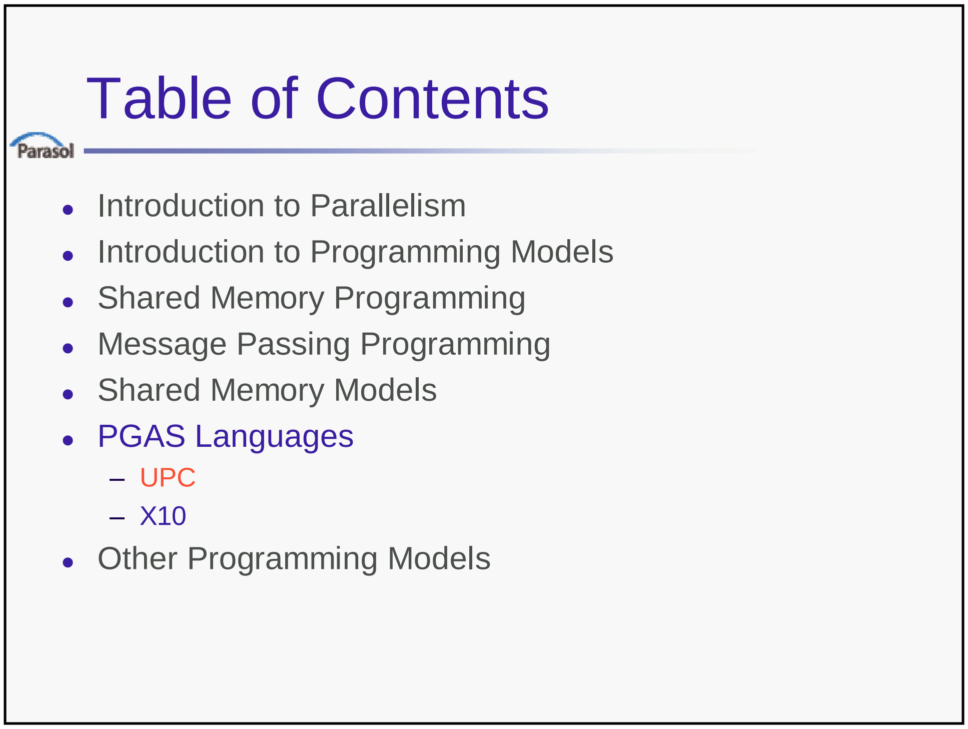

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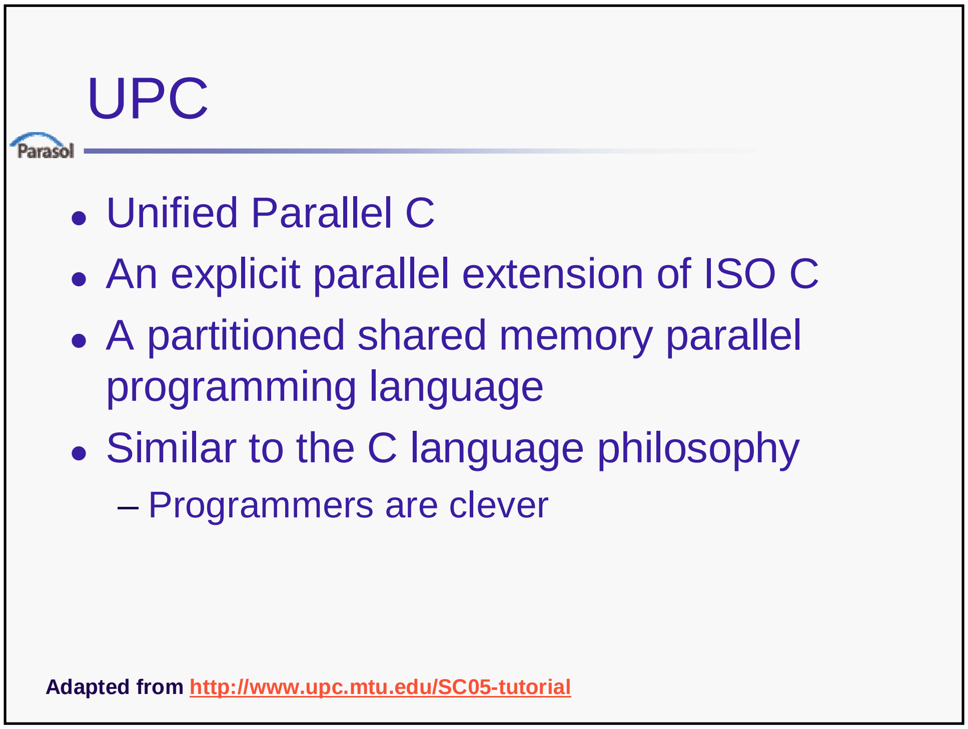


UPC

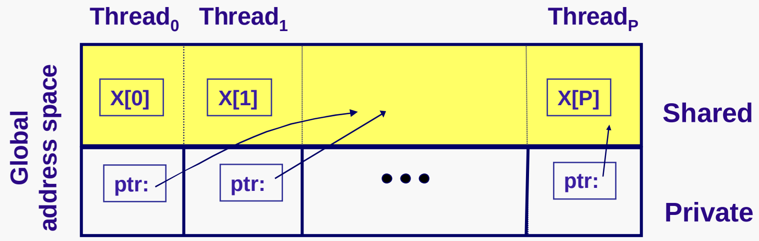
- Unified Parallel C
- An explicit parallel extension of ISO C
- A partitioned shared memory parallel programming language
- Similar to the C language philosophy
  - Programmers are clever

Adapted from http://www.upc.mtu.edu/SC05-tutorial

Execution Model

- UPC is SPMD
  - Number of threads specified at compile-time or run-time;
  - Available as program variable `THREADS`
  - `MYTHREAD` specifies thread index (`0..THREADS-1`)
- There are two compilation modes
  - Static Threads mode:
    - THREADS is specified at compile time by the user
    - THREADS as a compile-time constant
  - Dynamic threads mode:
    - Compiled code may be run with varying numbers of threads

UPC is PGAS



- The languages share the global address space abstraction
  - Programmer sees a single address space
  - Memory is logically partitioned by processors
  - There are only two types of references: local and remote
  - One-sided communication

Hello World

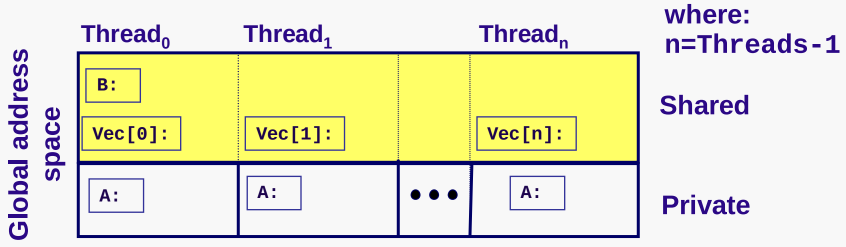
- Any legal C program is also a legal UPC program
- UPC with P threads will run P copies of the program.
- Multiple threads view

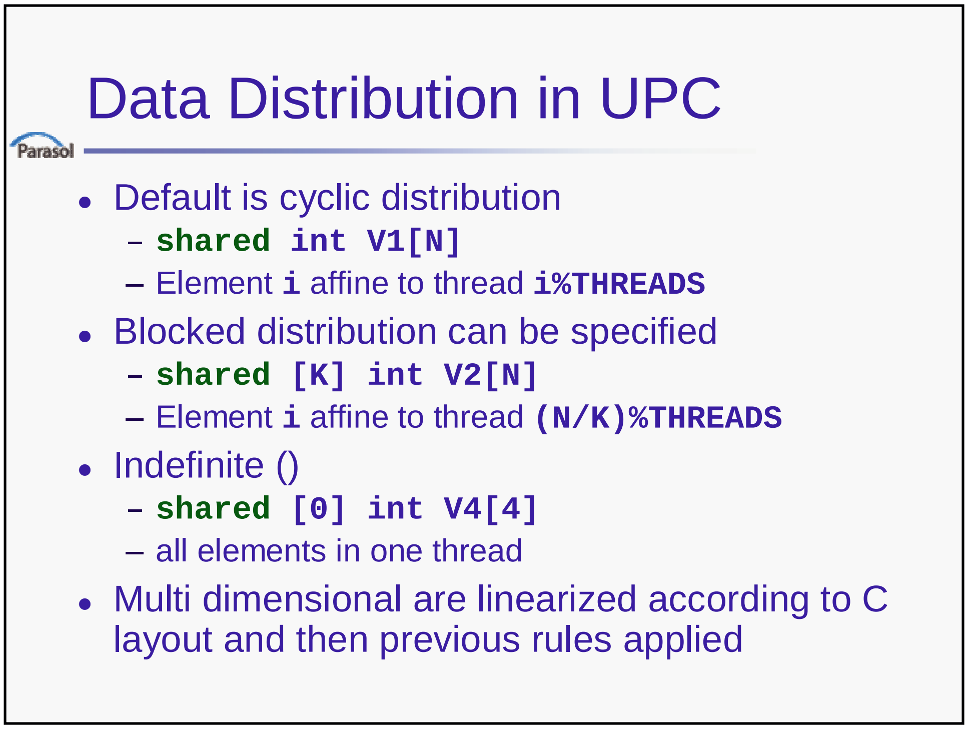
```
#include <upc.h>  /* UPC extensions */
#include <stdio.h>

main() {
  printf("Thread %d of %d: hello UPC
  world\n", \
         MYTHREAD, THREADS);
}
```

Private vs. Shared Variables

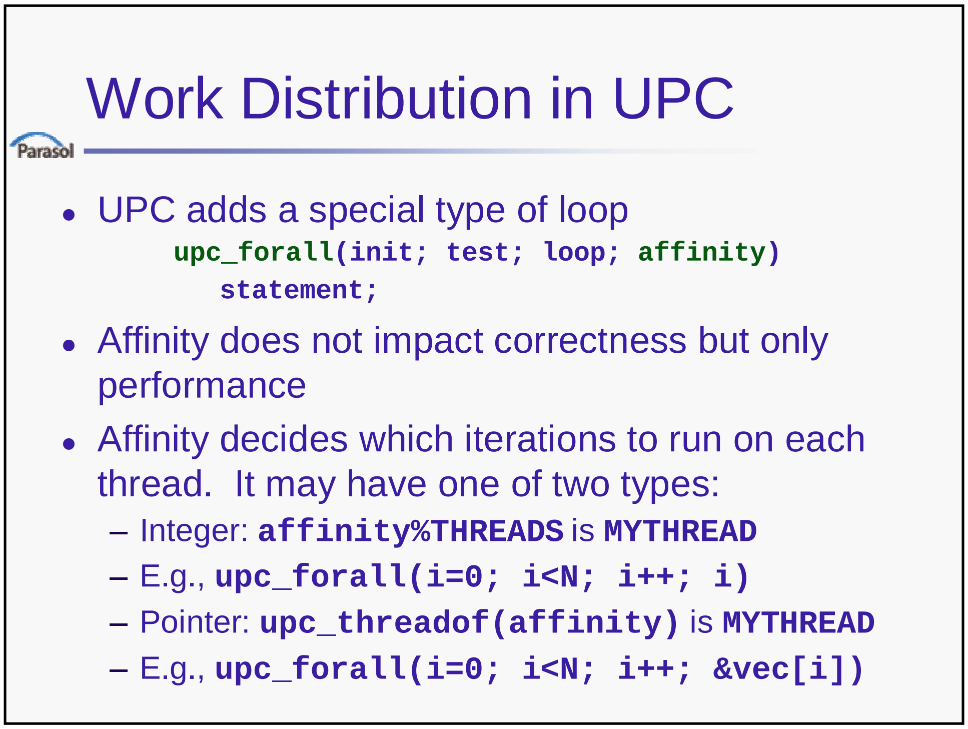
- Private scalars (**`int A`**)
- Shared scalars (**`shared int B`**)
- Shared arrays (**`shared int Vec[TREADS]`**)
- Shared Scalars are always in threads 0 space
- A variable local to a thread is said to be **affine** to that thread





Data Distribution in UPC

- Default is cyclic distribution
  - `shared int V1[N]`
  - Element `i` affine to thread `i%THREADS`
- Blocked distribution can be specified
  - `shared [K] int V2[N]`
  - Element `i` affine to thread `(N/K)%THREADS`
- Indefinite ()
  - `shared [0] int V4[4]`
  - all elements in one thread
- Multi dimensional are linearized according to C layout and then previous rules applied



Work Distribution in UPC

- UPC adds a special type of loop

```
upc_forall(init; test; loop; affinity)
   statement;
```

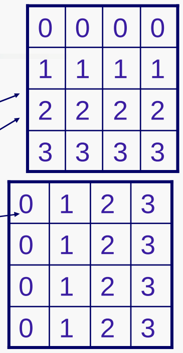
- Affinity does not impact correctness but only performance
- Affinity decides which iterations to run on each thread. It may have one of two types:
  - Integer: `affinity%THREADS` is `MYTHREAD`
  - E.g., `upc_forall(i=0; i<N; i++; i)`
  - Pointer: `upc_threadof(affinity)` is `MYTHREAD`
  - E.g., `upc_forall(i=0; i<N; i++; &vec[i])`

UPC Matrix Multiply

```
#define N 4
#define P 4
#define M 4
// Row-wise blocking:
shared [N*P/THREADS] int a[N][P], c[N][M];
// Column-wise blocking:
shared[M/THREADS] int b[P][M];

void main (void) {
  int i, j , l; // private variables

  upc_forall(i = 0 ; i<N ; i++; &c[i][0])
    for (j=0 ; j<M ;j++) {
      c[i][j] = 0;
      for (l= 0 ; l<P ; l++)
        c[i][j] += a[i][l]*b[l][j];
    }
}
```



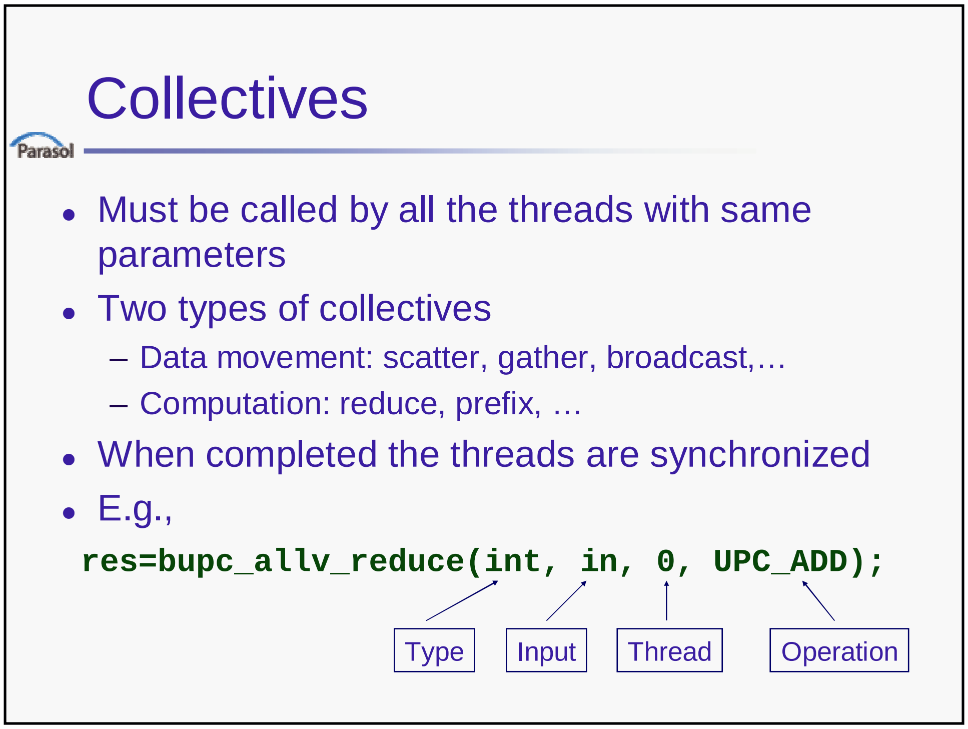
0	0	0	0
1	1	1	1
2	2	2	2
3	3	3	3

0	1	2	3
0	1	2	3
0	1	2	3
0	1	2	3

Replicating **b** among processors would improve performance

Synchronization and Locking

- Synchronization
  - Barrier: block until all other threads arrive
    - **upc_barrier**
  - Split-phase barriers
    - **upc_notify** this thread is ready for barrier
    - **upc_wait** wait for others to be ready
- Locks: **upc_lock_t**
  - Use to enclose critical regions
    - **void upc_lock(upc_lock_t *l)**
    - **void upc_unlock(upc_lock_t *l)**
  - Lock must be allocated before use

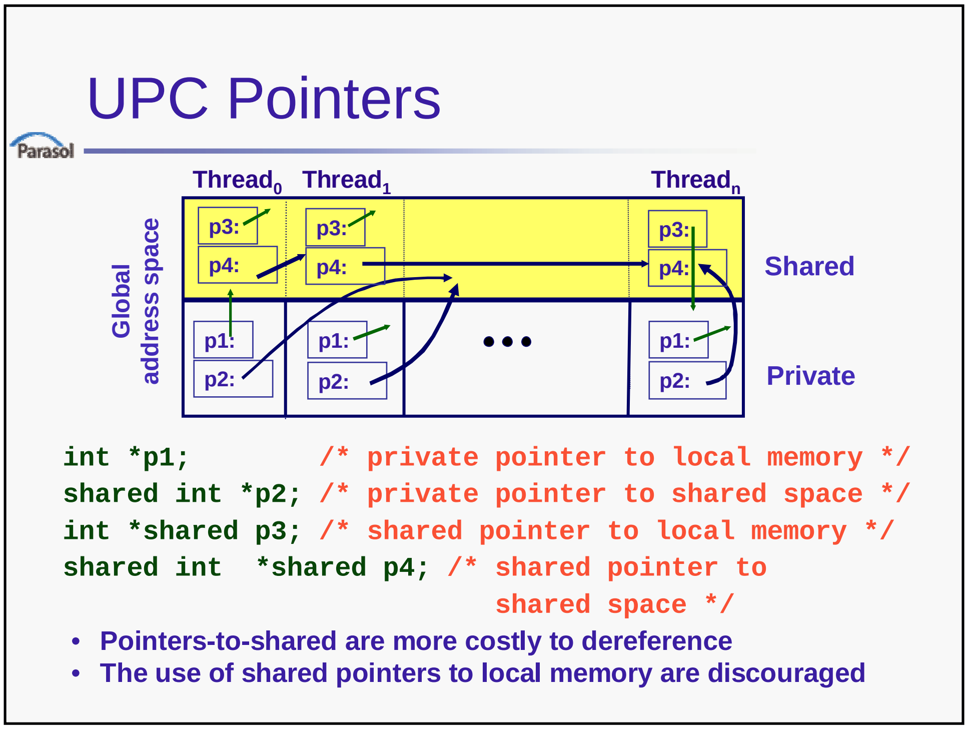


Collectives

- Must be called by all the threads with same parameters
- Two types of collectives
  - Data movement: scatter, gather, broadcast,…
  - Computation: reduce, prefix, …
- When completed the threads are synchronized
- E.g.,

```
res=bupc_allv_reduce(int, in, 0, UPC_ADD);
```

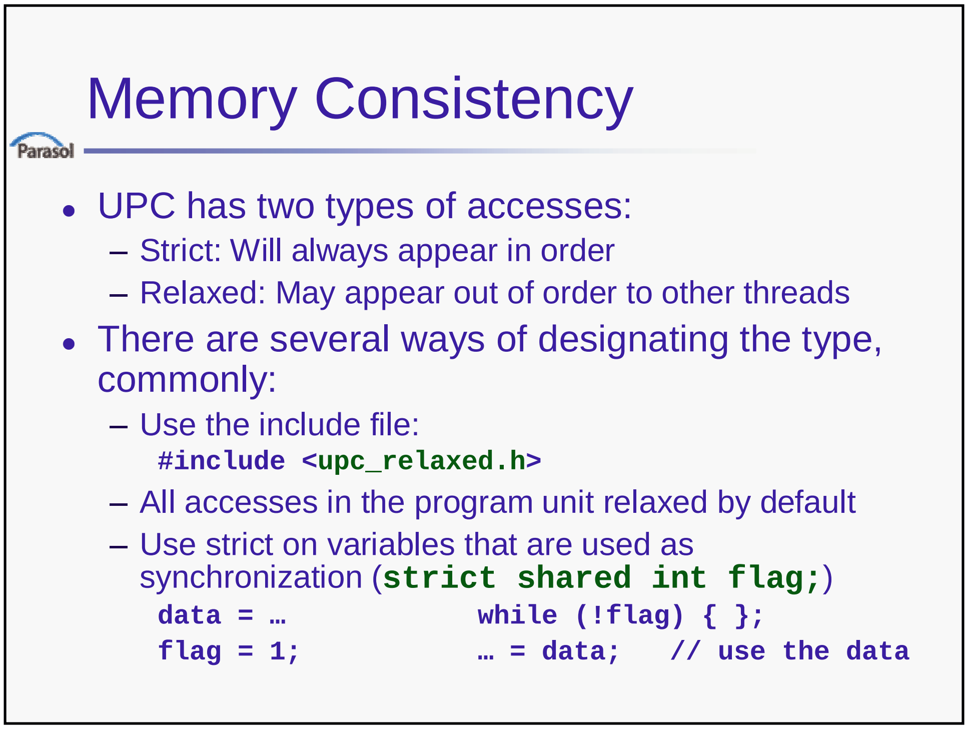
Type Input Thread Operation



UPC Pointers

```
int *p1;         /* private pointer to local memory */
shared int *p2; /* private pointer to shared space */
int *shared p3; /* shared pointer to local memory */
shared int  *shared p4; /* shared pointer to
                           shared space */
```

- **Pointers-to-shared are more costly to dereference**
- **The use of shared pointers to local memory are discouraged**



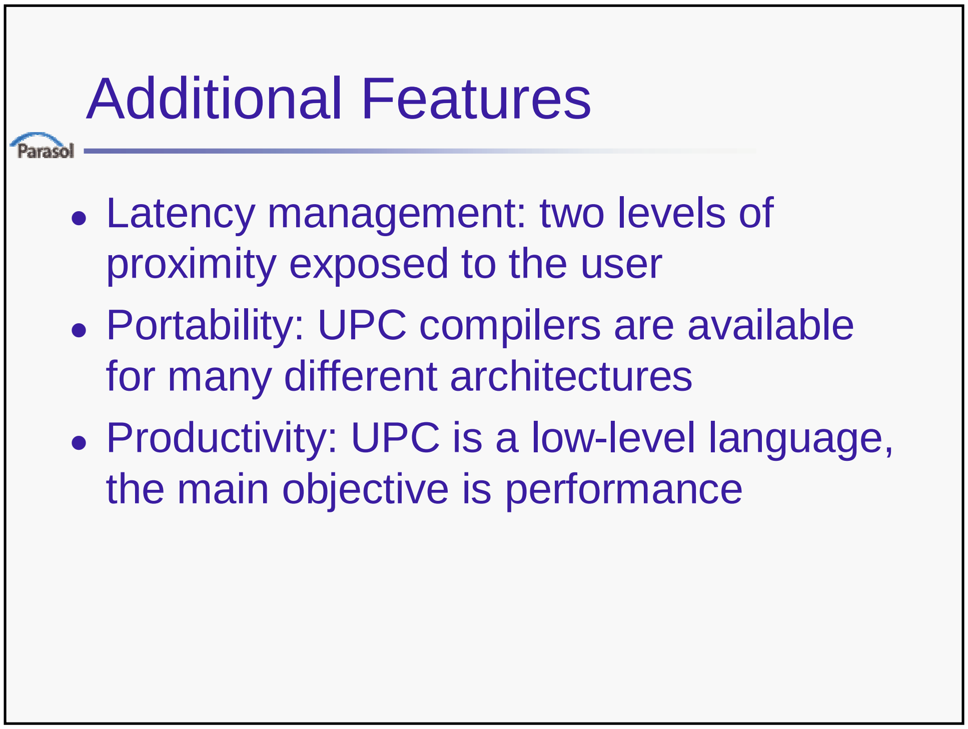
Memory Consistency

- UPC has two types of accesses:
  - Strict: Will always appear in order
  - Relaxed: May appear out of order to other threads
- There are several ways of designating the type, commonly:
  - Use the include file:

    ```
    #include <upc_relaxed.h>
    ```

  - All accesses in the program unit relaxed by default
  - Use strict on variables that are used as synchronization (`strict shared int flag;`)

    ```
    data = …             while (!flag) { };
    flag = 1;            … = data;   // use the data
    ```



Additional Features

- Latency management: two levels of proximity exposed to the user
- Portability: UPC compilers are available for many different architectures
- Productivity: UPC is a low-level language, the main objective is performance

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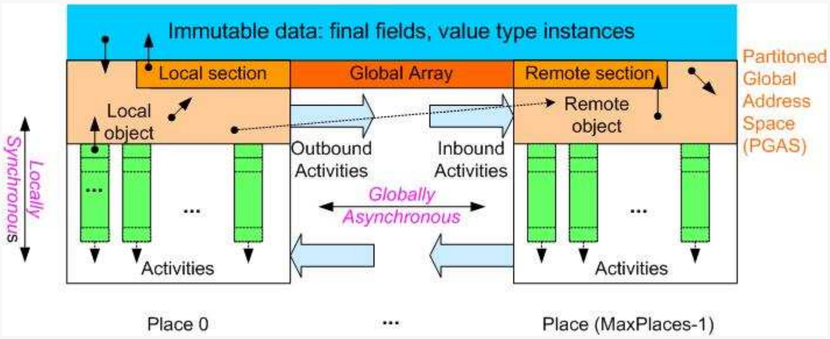
X10

- Developed by IBM as part of DARPA HPCS
- Draws from Java syntax and arrays in ZPL
- Partitioned Global Address Space (PGAS)
- Clocks - generalized barrier synchronization
- Constructs for explicit data and work placement

Adapted from presentations at: http://x10.sourceforge.net/tutorial/presentations

The X10 Model



Place - collection of resident activities & objects
(e.g., SMP node of cluster).

Activities - lightweight thread of execution.

Locality Rule
Access to data must be performed by a local activity.
Remote data accessed by creating remote activities

Ordering Constraints (Memory Model)
Locally Synchronous:
Guaranteed coherence for local heap.
Strict, near sequential consistency.

Globally Asynchronous:
No ordering of inter-place activities.
Explicit synchronization for coherence.

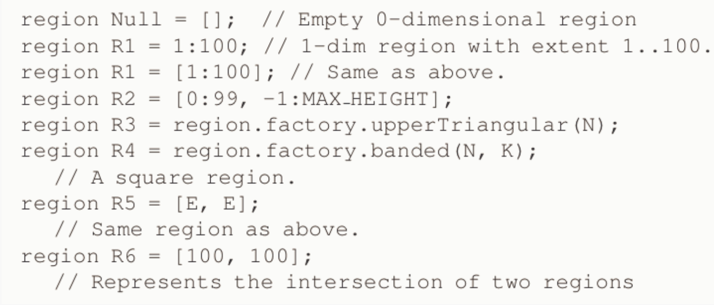
The X10 Model

Execution Model

- Explicit data parallelism, **`foreach`**
- Explicit task parallelism **`future`**, **`async`**
- Explicit, asynchronous, one-sided communication with **`future`**
- Explicit synchronization
  - **`clock`**, **`finish`**, **`future`**, **`atomic`** section (within a place)
- Multi-level memory model under development
  - Within a place - more strict, not quite sequential consistency
  - Across places - relaxed, explicit synchronization required

X10 - Regions

- Defines a set of *points* (indices)
  - Analogous to Chapel domains
  - User defined regions in development

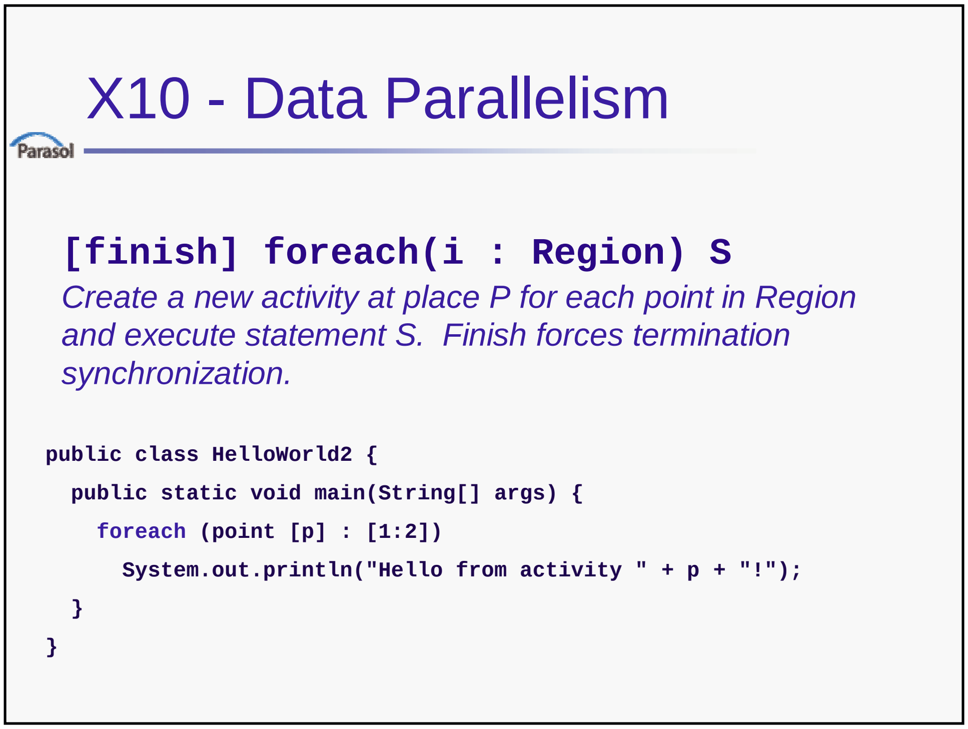


```
region Null = [];  // Empty 0-dimensional region
region R1 = 1:100; // 1-dim region with extent 1..100.
region R1 = [1:100]; // Same as above.
region R2 = [0:99, -1:MAX_HEIGHT];
region R3 = region.factory.upperTriangular(N);
region R4 = region.factory.banded(N, K);
   // A square region.
region R5 = [E, E];
   // Same region as above.
region R6 = [100, 100];
   // Represents the intersection of two regions
```

X10 - Distributions

- Maps every point in a region to a place
  - Analogous to Chapel distributed domains
  - User distributions regions in development

```
dist D1 = dist.factory.constant(R, here);//maps region R to local place
dist D2 = dist.factory.block(R);       //blocked distribution
dist D3 = dist.factory.cyclic(R);      //cyclic distribution
dist D4 = dist.factory.unique();       //identity map on [0:MAX_PLACES-1]

double[D] vals;
vals.distribution[i] //returns place where ith element is located.
```

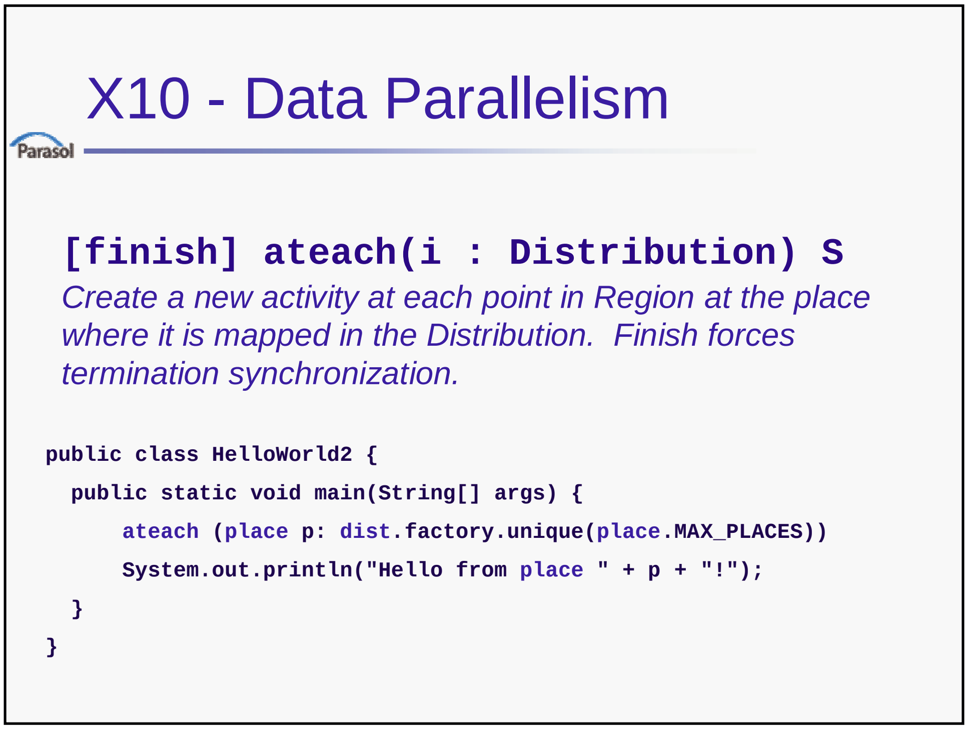


X10 - Data Parallelism

[finish] foreach(i : Region) S

Create a new activity at place P for each point in Region and execute statement S. Finish forces termination synchronization.

```
public class HelloWorld2 {
  public static void main(String[] args) {
    foreach (point [p] : [1:2])
      System.out.println("Hello from activity " + p + "!");
  }
}
```

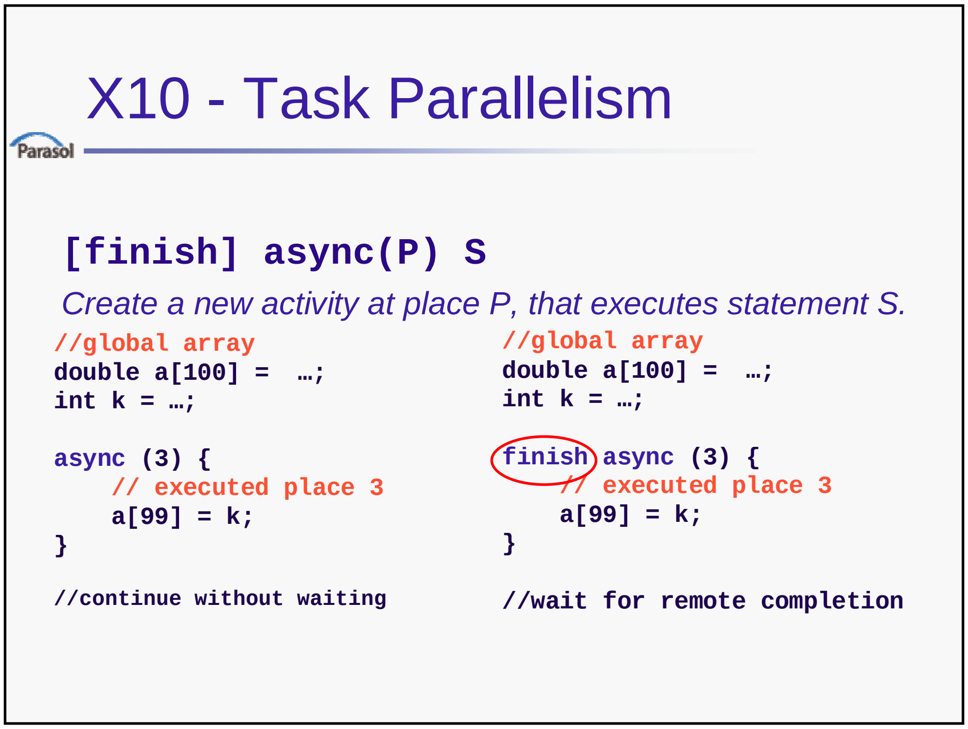


X10 - Data Parallelism

[finish] ateach(i : Distribution) S

Create a new activity at each point in Region at the place where it is mapped in the Distribution. Finish forces termination synchronization.

```
public class HelloWorld2 {
  public static void main(String[] args) {
      ateach (place p: dist.factory.unique(place.MAX_PLACES))
      System.out.println("Hello from place " + p + "!");
  }
}
```



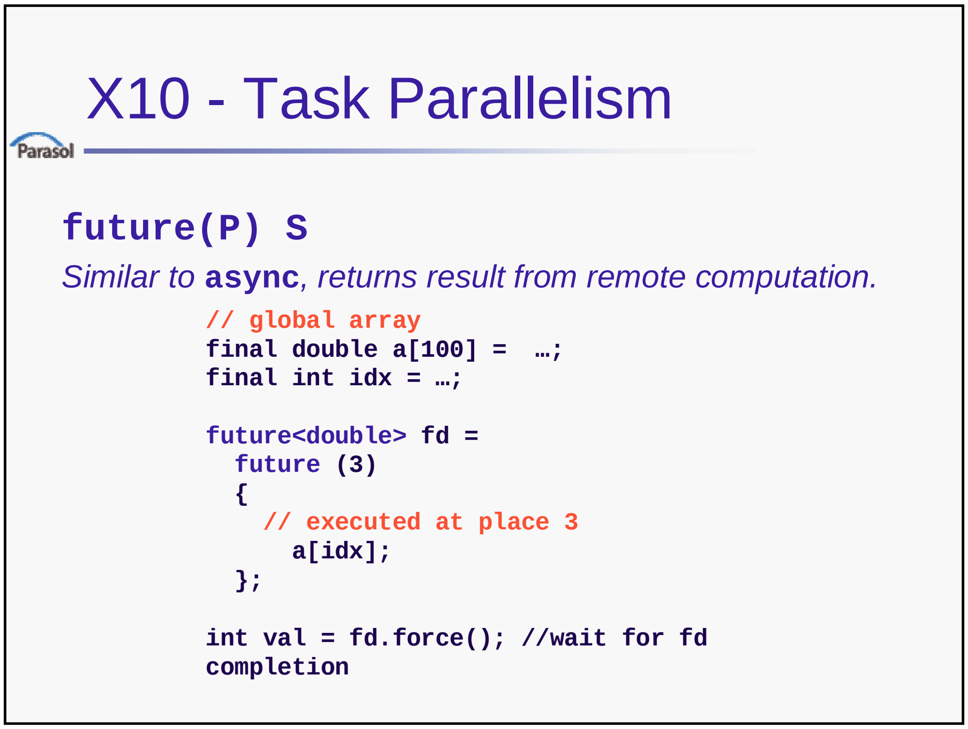
X10 - Task Parallelism

[finish] async(P) S

Create a new activity at place P, that executes statement S.

```
//global array
double a[100] =  …;
int k = …;

async (3) {
    // executed place 3
    a[99] = k;
}

//continue without waiting
```

```
//global array
double a[100] =  …;
int k = …;

finish async (3) {
    // executed place 3
    a[99] = k;
}

//wait for remote completion
```

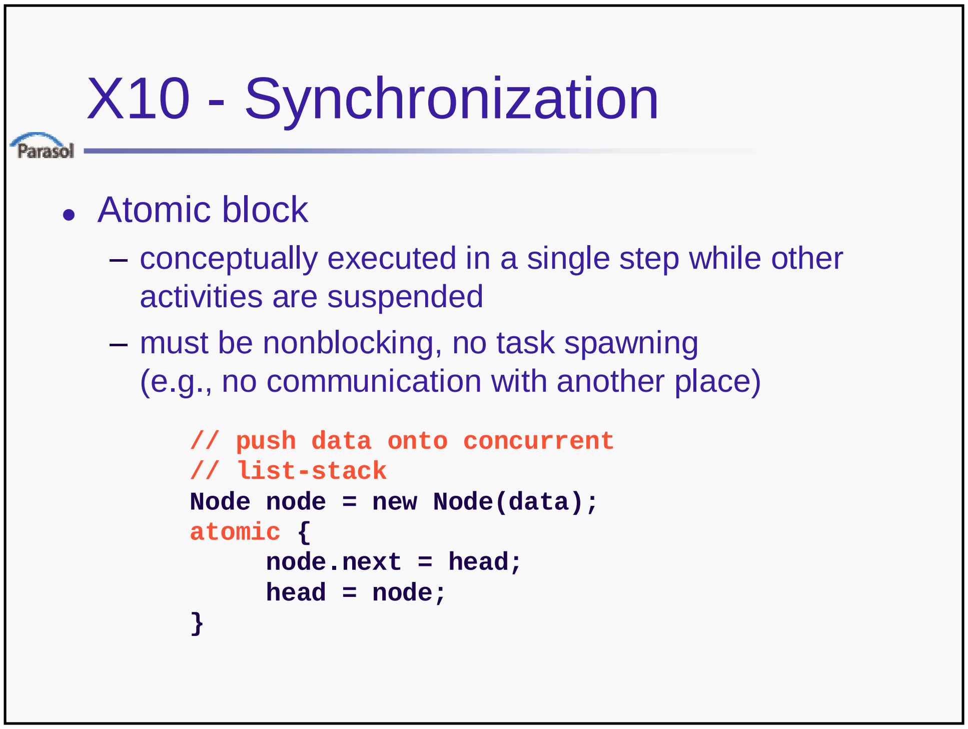


X10 - Task Parallelism

future(P) S

Similar to **async**, *returns result from remote computation.*

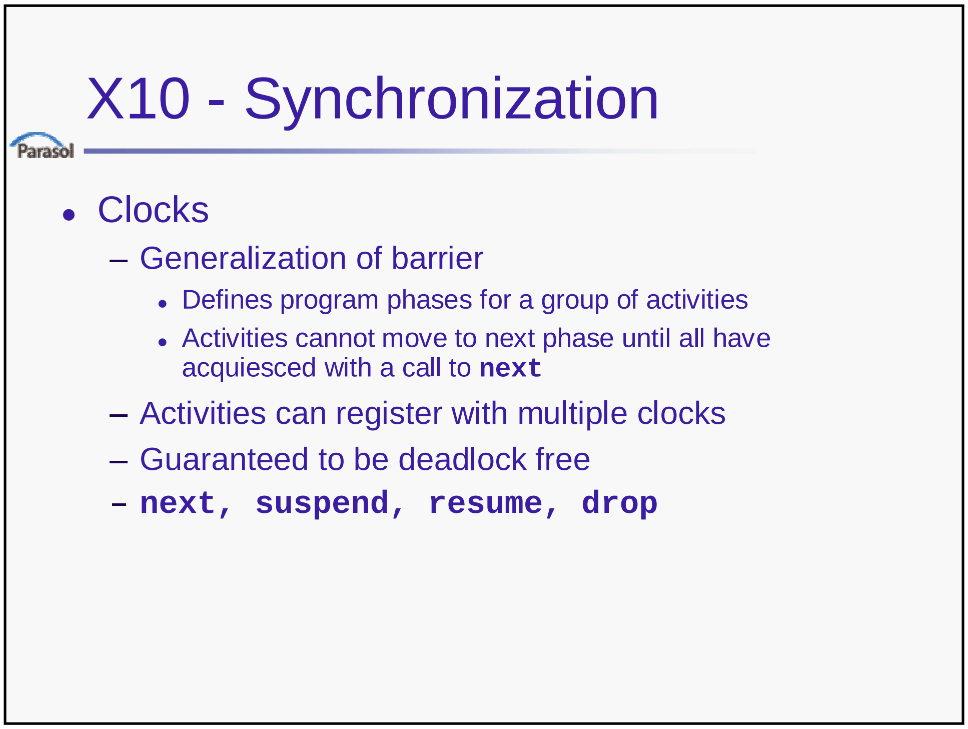
```
// global array
final double a[100] =  …;
final int idx = …;

future<double> fd =
  future (3)
  {
    // executed at place 3
      a[idx];
  };

int val = fd.force(); //wait for fd
completion
```



X10 - Synchronization

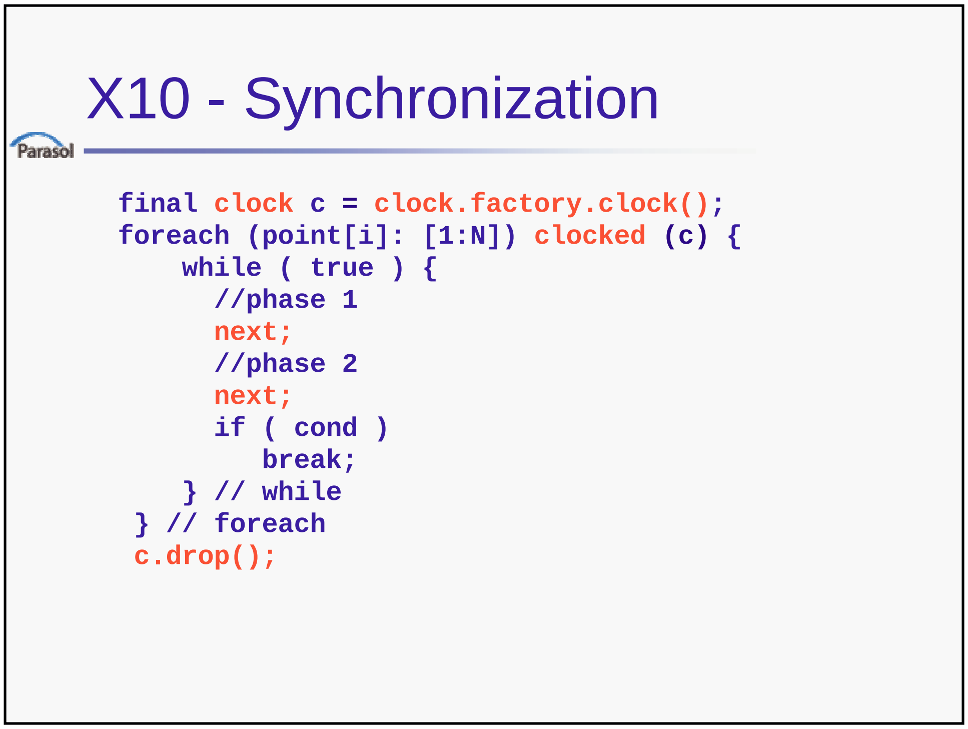
- Atomic block
  - conceptually executed in a single step while other activities are suspended
  - must be nonblocking, no task spawning (e.g., no communication with another place)

```
// push data onto concurrent
// list-stack
Node node = new Node(data);
atomic {
     node.next = head;
     head = node;
}
```



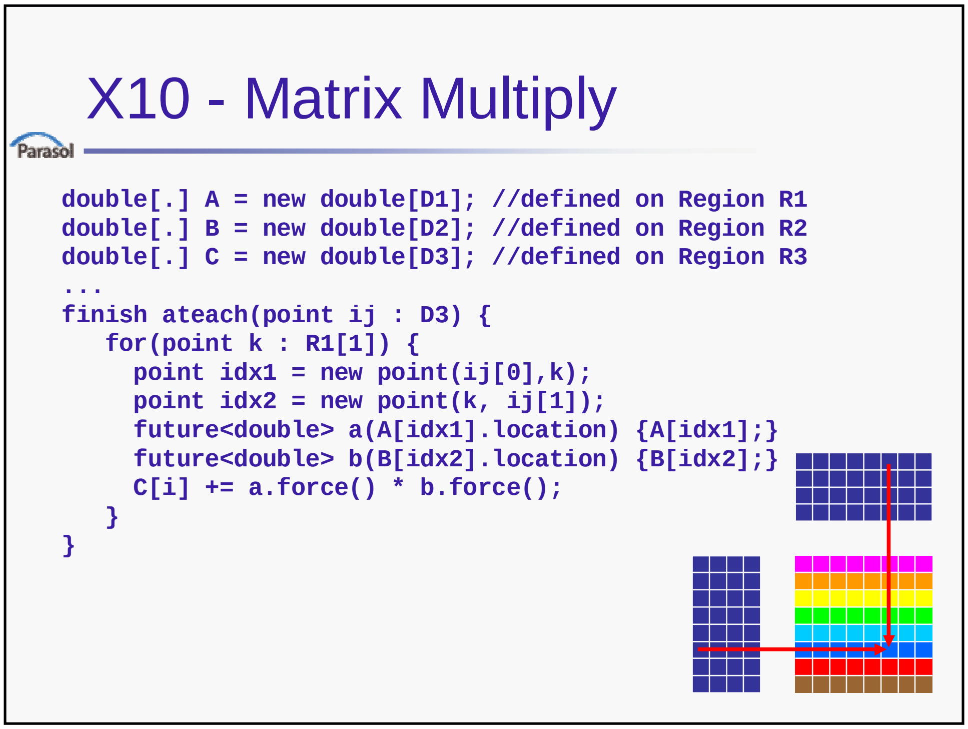
X10 - Synchronization

- Clocks
  - Generalization of barrier
    - Defines program phases for a group of activities
    - Activities cannot move to next phase until all have acquiesced with a call to **next**
  - Activities can register with multiple clocks
  - Guaranteed to be deadlock free
  - **next, suspend, resume, drop**



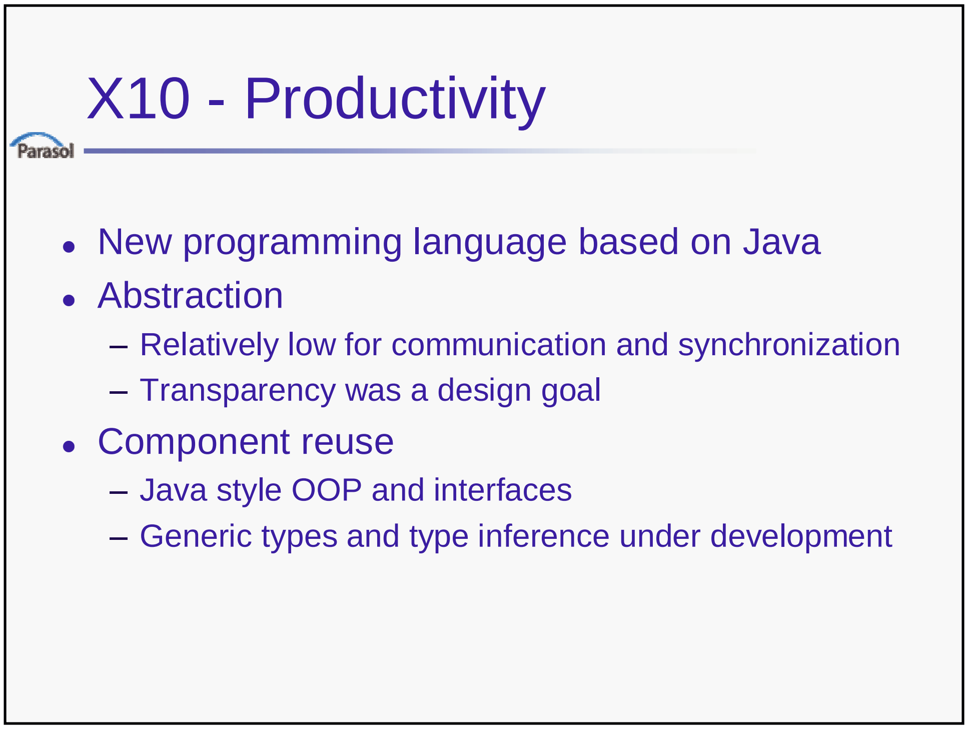
X10 - Synchronization

```
final clock c = clock.factory.clock();
foreach (point[i]: [1:N]) clocked (c) {
    while ( true ) {
      //phase 1
      next;
      //phase 2
      next;
      if ( cond )
         break;
    } // while
 } // foreach
 c.drop();
```



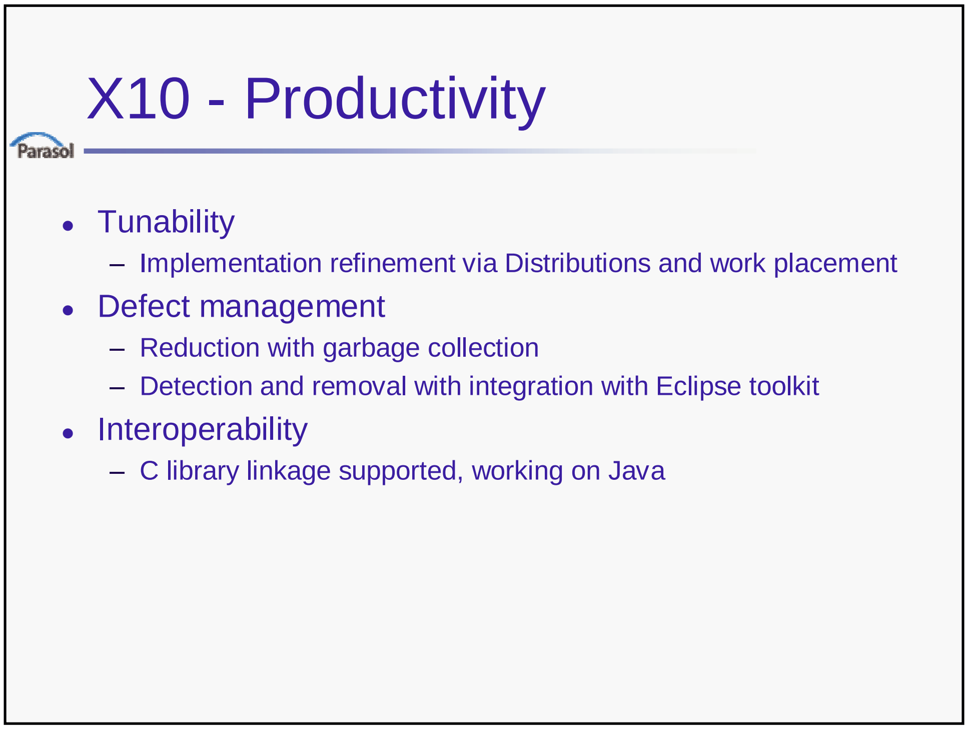
X10 - Matrix Multiply

```
double[.] A = new double[D1]; //defined on Region R1
double[.] B = new double[D2]; //defined on Region R2
double[.] C = new double[D3]; //defined on Region R3
...
finish ateach(point ij : D3) {
   for(point k : R1[1]) {
     point idx1 = new point(ij[0],k);
     point idx2 = new point(k, ij[1]);
     future<double> a(A[idx1].location) {A[idx1];}
     future<double> b(B[idx2].location) {B[idx2];}
     C[i] += a.force() * b.force();
   }
}
```



X10 - Productivity

- New programming language based on Java
- Abstraction
  - Relatively low for communication and synchronization
  - Transparency was a design goal
- Component reuse
  - Java style OOP and interfaces
  - Generic types and type inference under development



X10 - Productivity

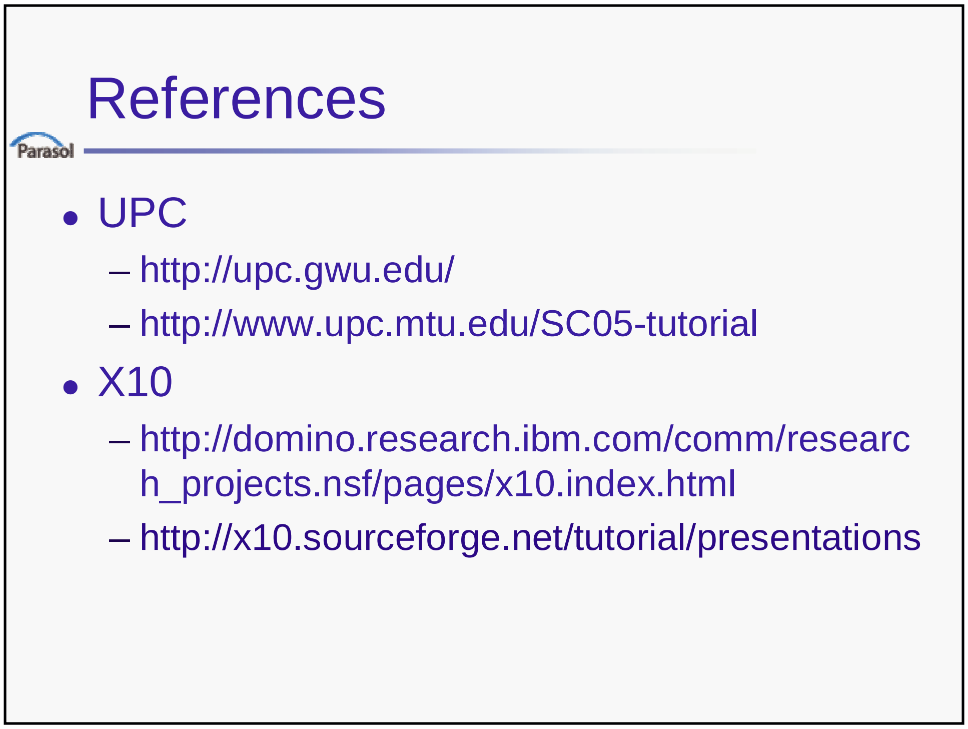
- Tunability
  - Implementation refinement via Distributions and work placement
- Defect management
  - Reduction with garbage collection
  - Detection and removal with integration with Eclipse toolkit
- Interoperability
  - C library linkage supported, working on Java

X10 - Performance

- Latency Management
  - Reducing
    - Data placement - distributions.
    - Work placement - `ateach, future, async`
  - Hiding
    - Asynchronous communication with `future`
    - Processor virtualization with activities
- Load Balancing
  - Runtime can schedule activities within a place

X10 - Portability

- Language based solution, requires compiler
- Runtime system not discussed. Must handle threading and communication - assumed to be part of model implementation
- **places** machine information available to programmer
- Parallel model not effected by underlying machine
- I/O not addressed in standard yet



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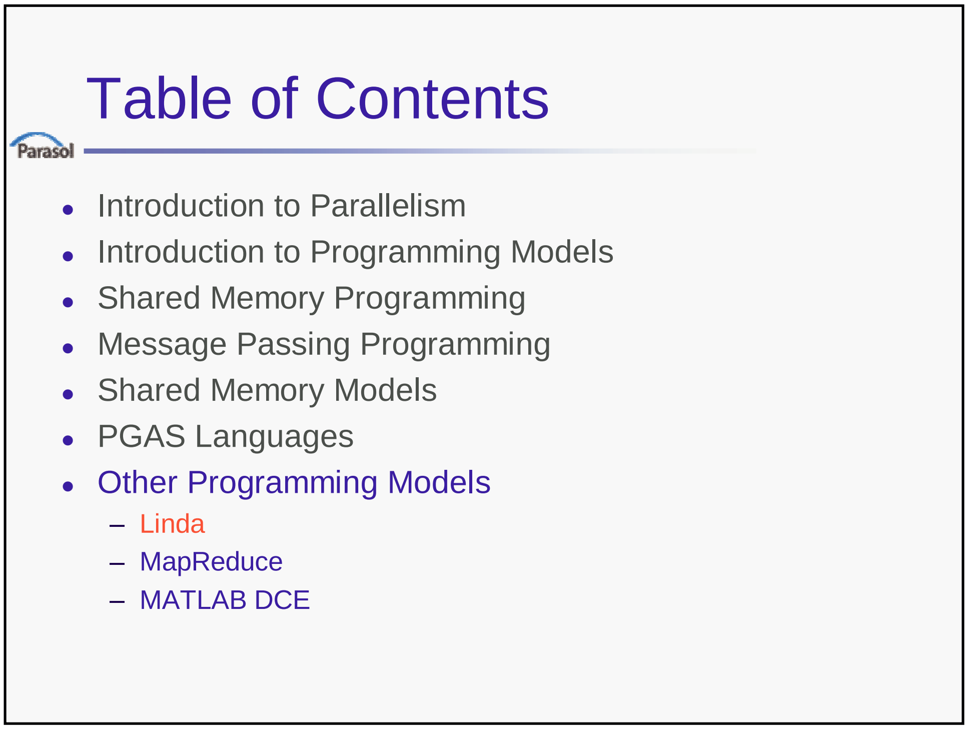

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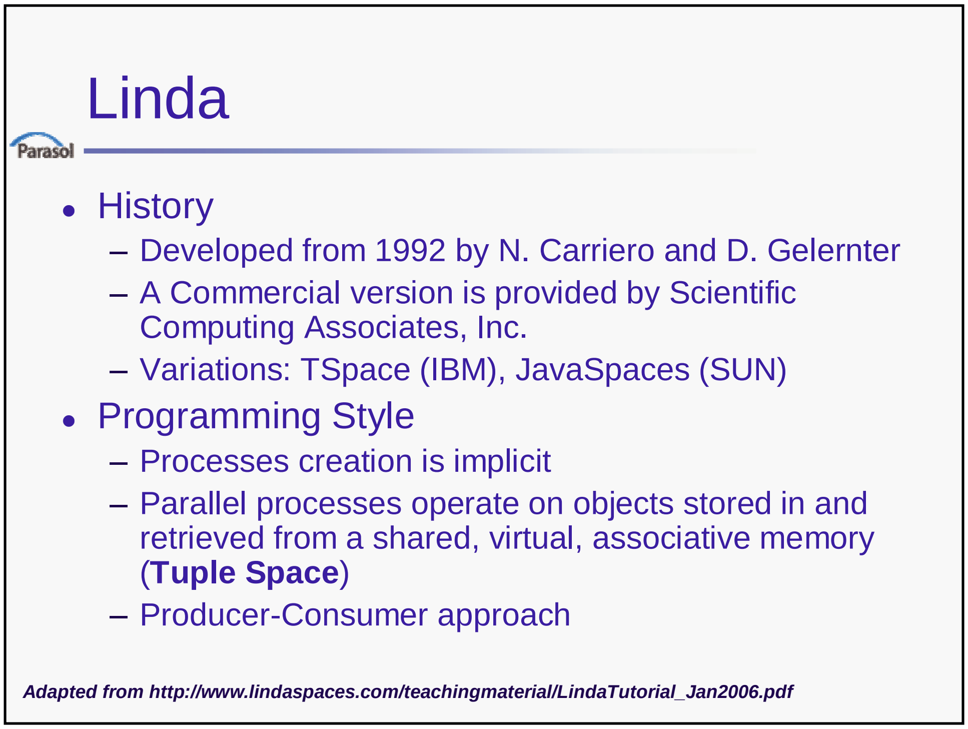
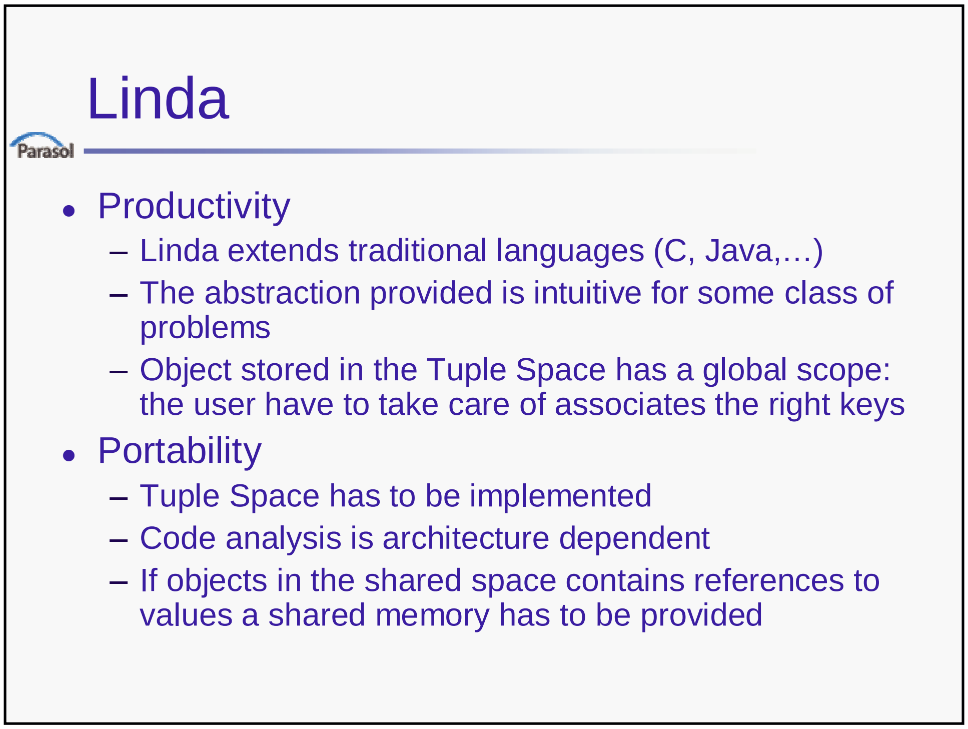


Linda

- History
  - Developed from 1992 by N. Carriero and D. Gelernter
  - A Commercial version is provided by Scientific Computing Associates, Inc.
  - Variations: TSpace (IBM), JavaSpaces (SUN)
- Programming Style
  - Processes creation is implicit
  - Parallel processes operate on objects stored in and retrieved from a shared, virtual, associative memory (**Tuple Space**)
  - Producer-Consumer approach

Adapted from http://www.lindaspaces.com/teachingmaterial/LindaTutorial_Jan2006.pdf



Linda

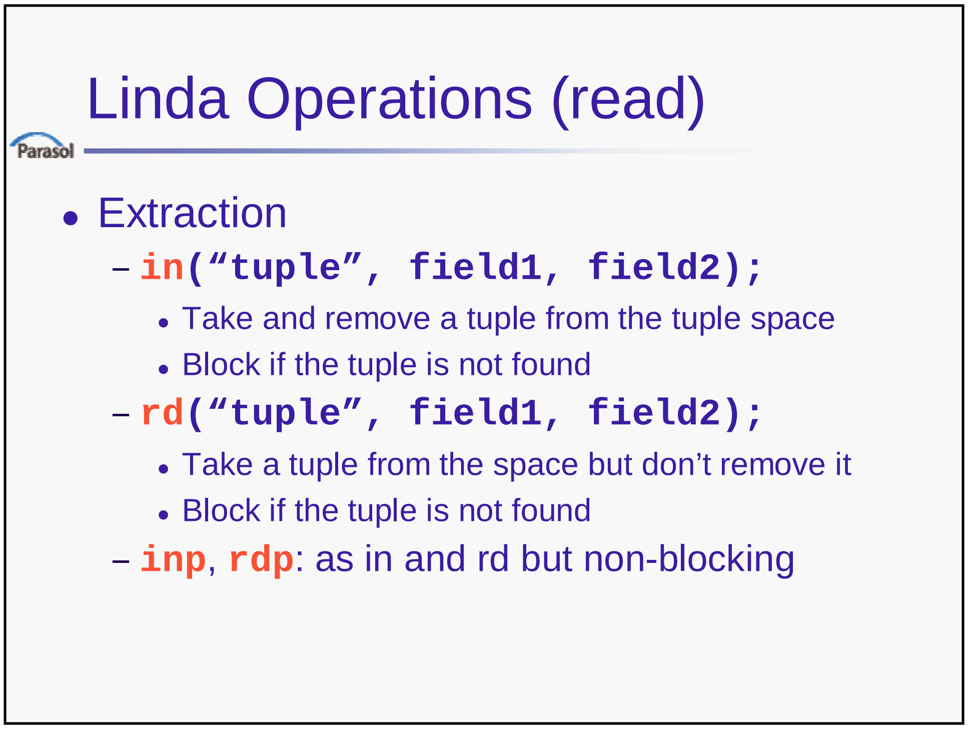
- Productivity
  - Linda extends traditional languages (C, Java,…)
  - The abstraction provided is intuitive for some class of problems
  - Object stored in the Tuple Space has a global scope: the user have to take care of associates the right keys
- Portability
  - Tuple Space has to be implemented
  - Code analysis is architecture dependent
  - If objects in the shared space contains references to values a shared memory has to be provided

Linda

- Performance
  - – Depends on Tuple Space implementation
    - Architecture is hidden to the user
  - – Code analysis can provide optimizations
- Defect analysis
  - – Commercial implementation provides debuggers and profilers

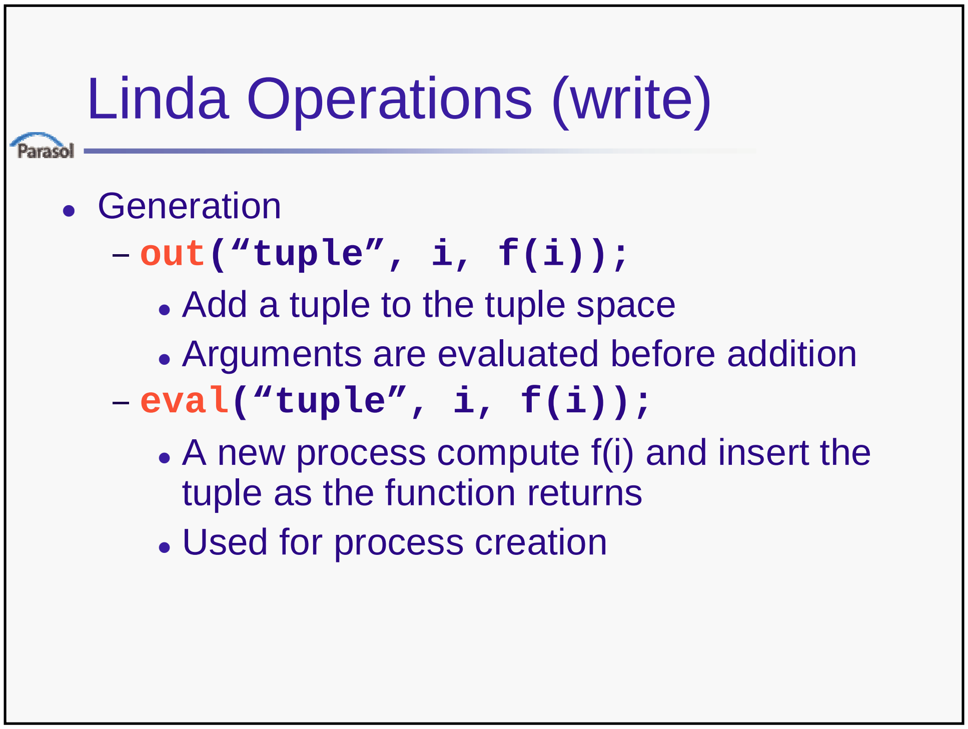
Tuple Space

- A Tuple is a sequence of typed fields:
    - ("Linda", 2, 32.5, 62)
    - (1,2, "A string", a:20) // array with size
    - ("Spawn", i, f(i))
- A Tuple Space is a repository of tuples
- Provide:
    - Process creation
    - Synchronization
    - Data communication
    - Platform independence



Linda Operations (read)

- Extraction
  - `in("tuple", field1, field2);`
    - Take and remove a tuple from the tuple space
    - Block if the tuple is not found
  - `rd("tuple", field1, field2);`
    - Take a tuple from the space but don't remove it
    - Block if the tuple is not found
  - `inp`, `rdp`: as in and rd but non-blocking



Linda Operations (write)

- Generation
  - `out("tuple", i, f(i));`
    - Add a tuple to the tuple space
    - Arguments are evaluated before addition
  - `eval("tuple", i, f(i));`
    - A new process compute f(i) and insert the tuple as the function returns
    - Used for process creation

Tuple matching

- Tuples are retrieved by matching
  - `out(“Hello”, 100)`
  - `in(“Hello”, 100) // match the tuple`
  - `in(“Hello”, ?i) // i=100`
- Tuples matching is non-deterministic
  - `out(“Hello”, 100)`
  - `out(“Hello”, 99)`
  - `in(“Hello”, ?i) // i=99 or i=100`
- Tuple and template must have the same number of fields and the same types

Atomicity

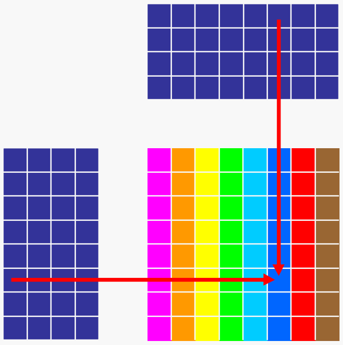
- The six Linda operations are atomic
  - A simple counter

    ```
    in(“counter”, ?count);
    out(“counter”, count+1);
    ```
  - The first operation remove the tuple gaining exclusive access to the counter
  - The second operation release the counter

Hello world

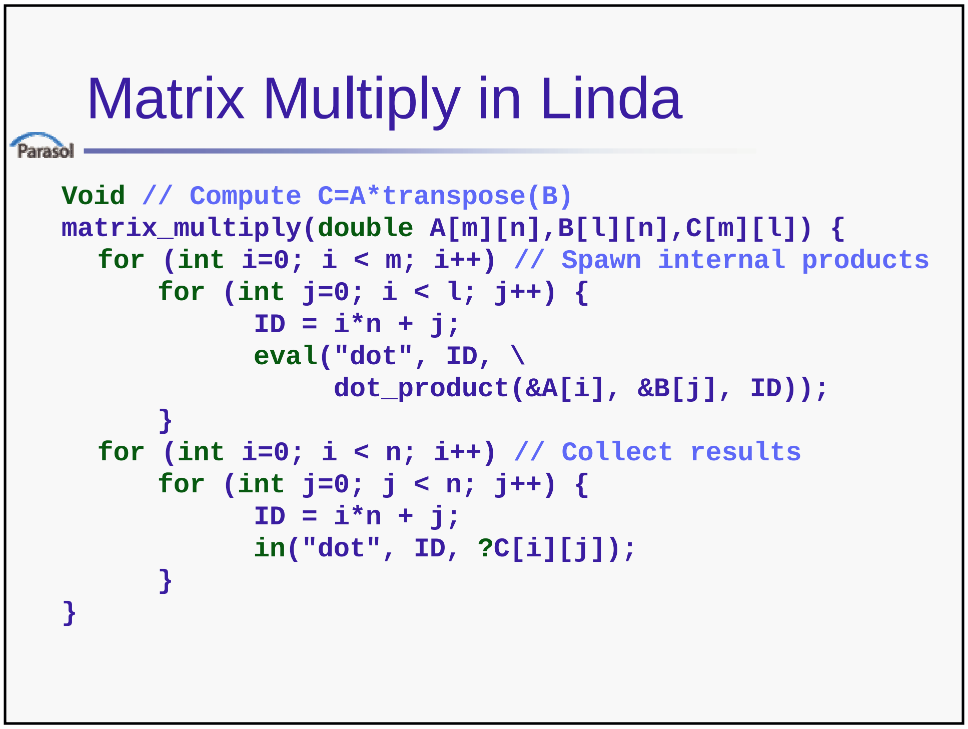
```
linda_main(int i) {
  out("count", 0);
  for(int i=1; i<=NUM_PROCS; i++)
      eval("worker",hello_world(i));
  in("count", NUM_PROCS);
  printf("All processes done.\n");
}

void hello_world (int i) {
  int j;
  in("count", ?j); out("count", j+1);
  printf("Hello world from process %d,", i);
  printf(" count %d\n", j);
}
```

Matrix Multiply



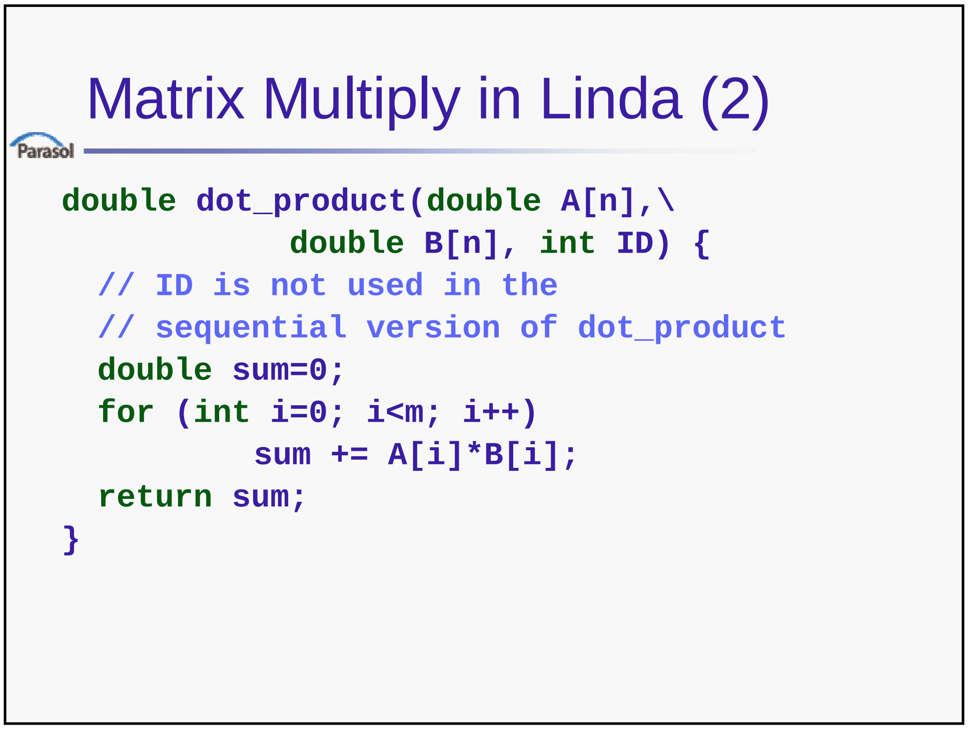
```
for(int i=0; i<M; ++i) {
  for(int k=0; k<L; ++k) {
    for(int j=0; j<N; ++j) {
      C[i][j] =
          A[i][k]*B[k][j];
    }
  }
}
```

A parallel specification:
C_{ij}* is the dot-product of row *i* of *A* and column *j* of *B



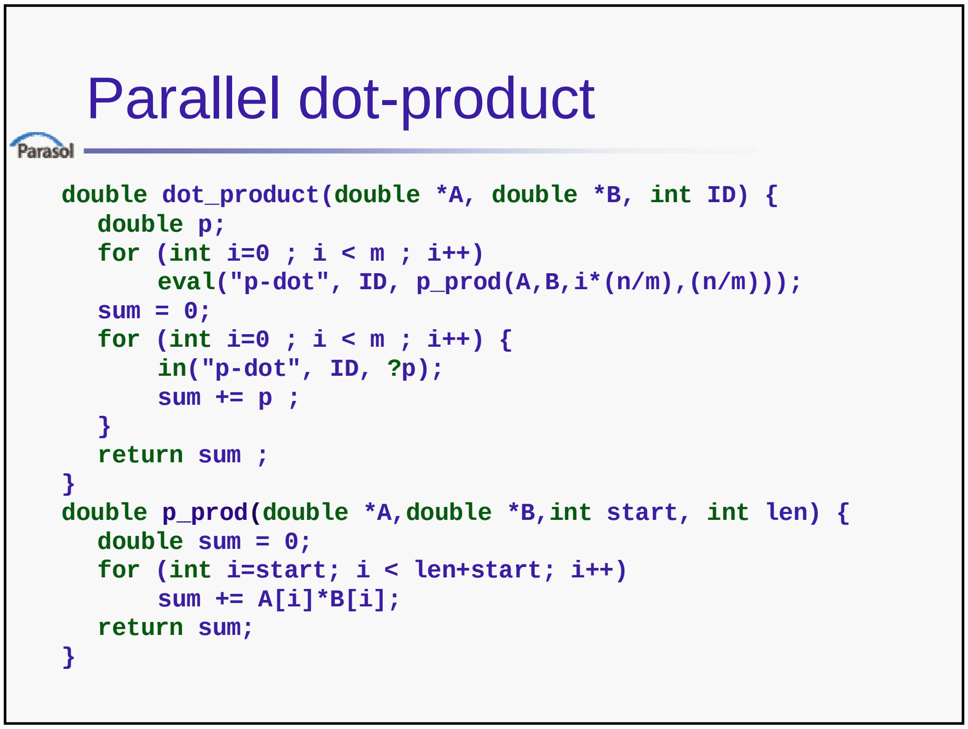
Matrix Multiply in Linda

```
Void // Compute C=A*transpose(B)
matrix_multiply(double A[m][n],B[l][n],C[m][l]) {
  for (int i=0; i < m; i++) // Spawn internal products
     for (int j=0; i < l; j++) {
          ID = i*n + j;
          eval("dot", ID, \
              dot_product(&A[i], &B[j], ID));
     }
  for (int i=0; i < n; i++) // Collect results
     for (int j=0; j < n; j++) {
          ID = i*n + j;
          in("dot", ID, ?C[i][j]);
     }
}
```



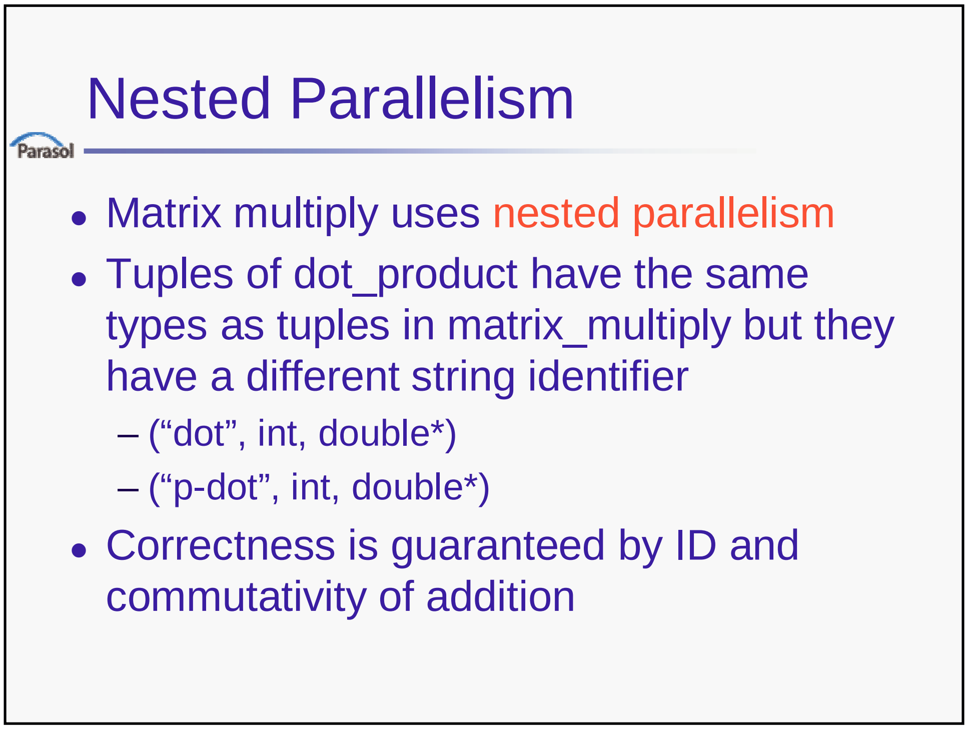
Matrix Multiply in Linda (2)

```
double dot_product(double A[n],\
            double B[n], int ID) {
  // ID is not used in the
  // sequential version of dot_product
  double sum=0;
  for (int i=0; i<m; i++)
          sum += A[i]*B[i];
  return sum;
}
```



Parallel dot-product

```
double dot_product(double *A, double *B, int ID) {
   double p;
   for (int i=0 ; i < m ; i++)
       eval("p-dot", ID, p_prod(A,B,i*(n/m),(n/m)));
   sum = 0;
   for (int i=0 ; i < m ; i++) {
       in("p-dot", ID, ?p);
       sum += p ;
   }
   return sum ;
}
double p_prod(double *A,double *B,int start, int len) {
   double sum = 0;
   for (int i=start; i < len+start; i++)
       sum += A[i]*B[i];
   return sum;
}
```



Nested Parallelism

- Matrix multiply uses nested parallelism
- Tuples of dot_product have the same types as tuples in matrix_multiply but they have a different string identifier
  - ("dot", int, double*)
  - ("p-dot", int, double*)
- Correctness is guaranteed by ID and commutativity of addition

Runtime

- Tuple rehashing
  - Runtime observe patterns of usage, remaps tuple to locations
    - Domain decomposition
    - Result tuples
    - Owner compute
- Long fields handling
  - Usually long fields are not used for mathcing
  - Bulk transfer
- Knowing implementation and architecture details and helps in optimizing user code

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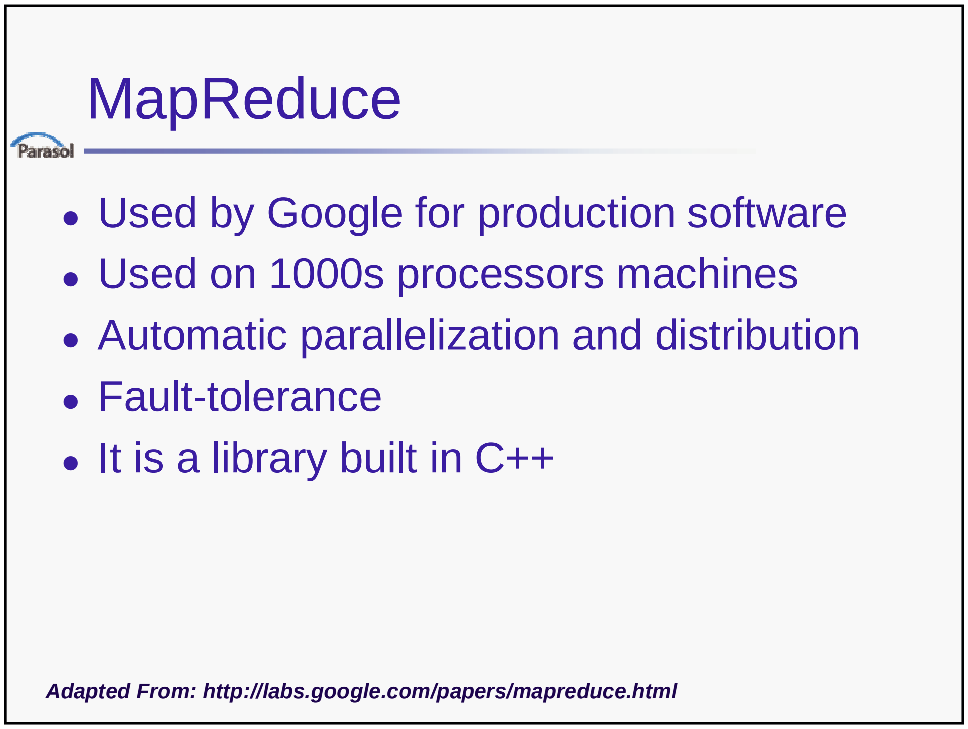
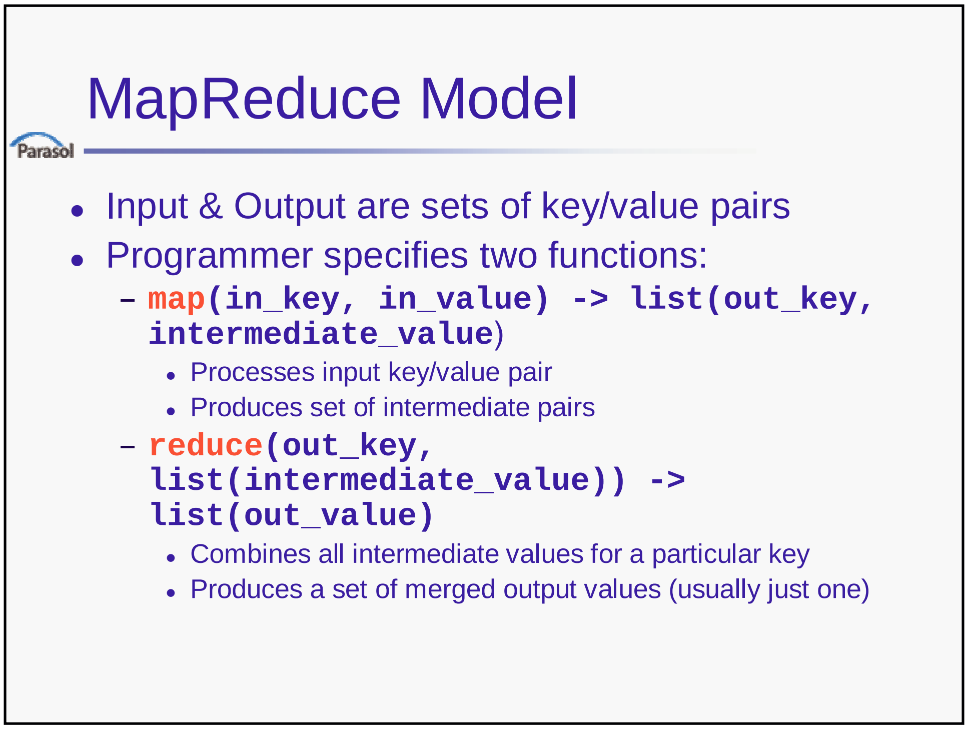


MapReduce

- Used by Google for production software
- Used on 1000s processors machines
- Automatic parallelization and distribution
- Fault-tolerance
- It is a library built in C++

Adapted From: http://labs.google.com/papers/mapreduce.html



MapReduce Model

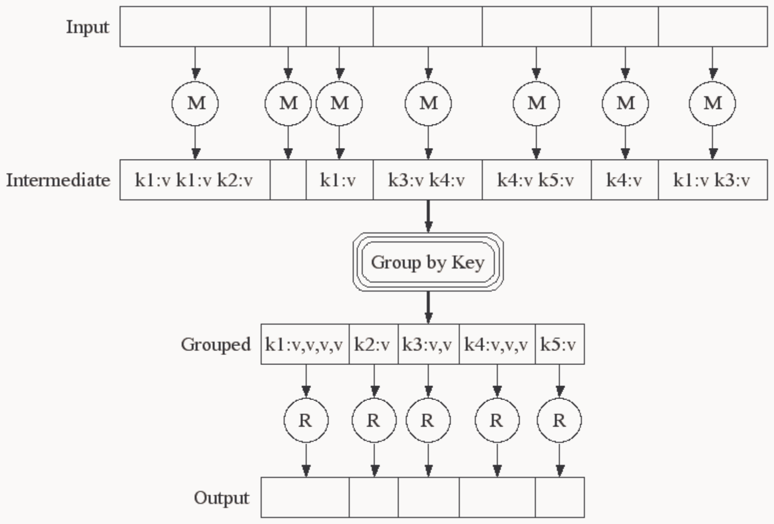
- Input & Output are sets of key/value pairs
- Programmer specifies two functions:
  - `map(in_key, in_value) -> list(out_key, intermediate_value)`
    - Processes input key/value pair
    - Produces set of intermediate pairs
  - `reduce(out_key, list(intermediate_value)) -> list(out_value)`
    - Combines all intermediate values for a particular key
    - Produces a set of merged output values (usually just one)

Example: Word Count

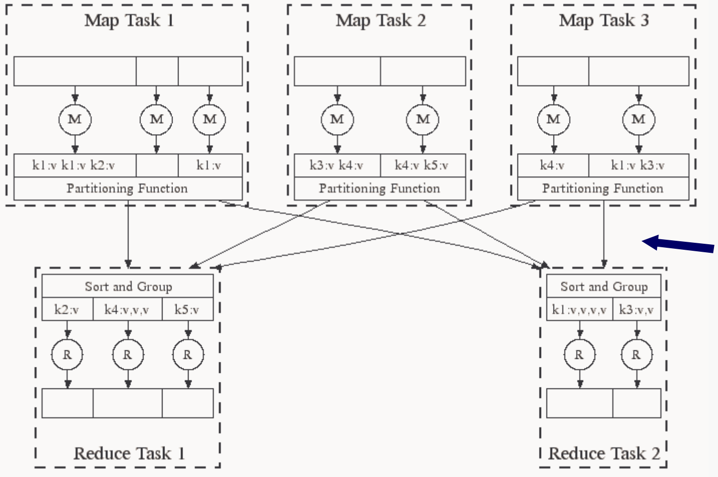
```
map(String input_key, String input_value):
  // input_key: document name
  // input_value: document contents
  for each word w in input_value:
      EmitIntermediate(w, "1");

reduce(String output_key, Iterator
  intermediate_values):
  // output_key: a word
  // output_values: a list of counts
  int result = 0; for each v in
  intermediate_values: result += ParseInt(v);
  Emit(AsString(result));
```

Sequential Execution Model



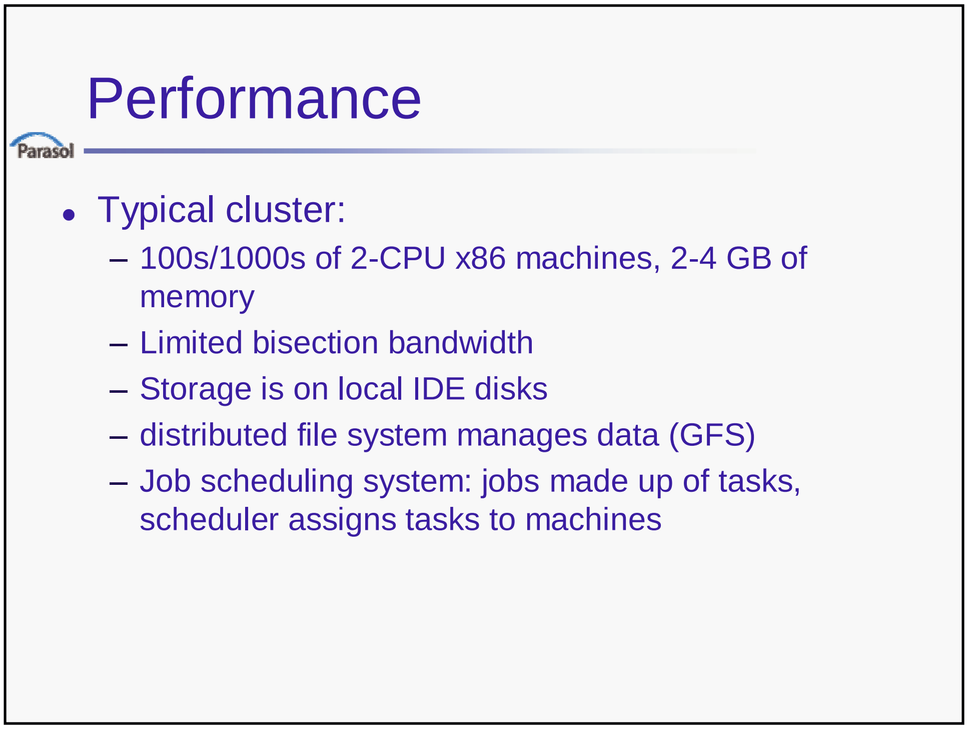
Parallel Execution Model



Shuffling & Sorting

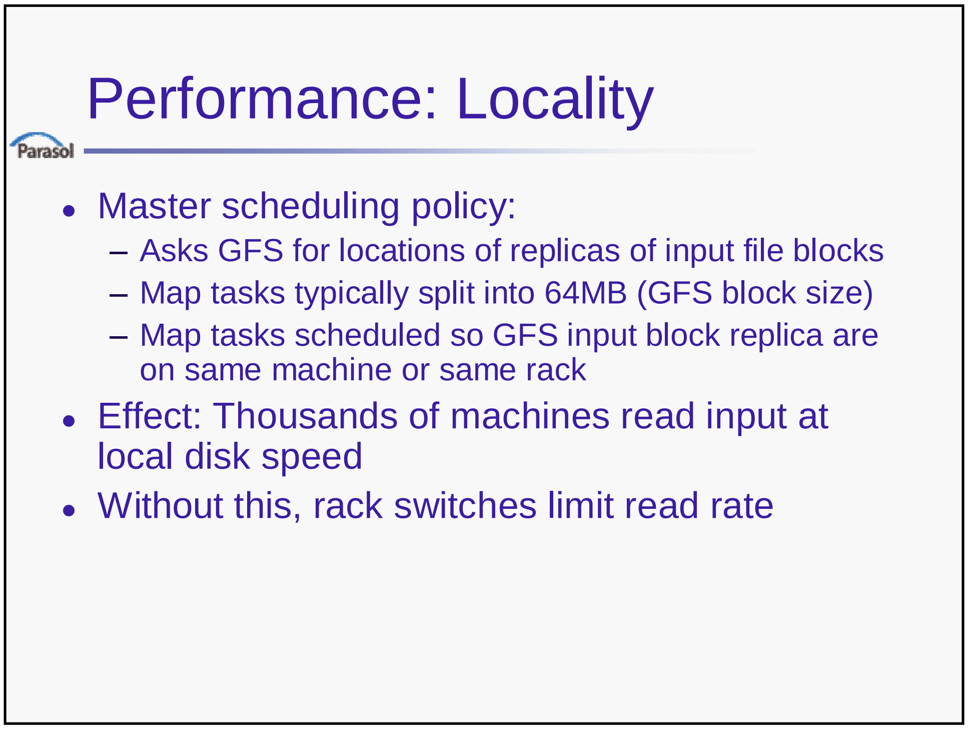
Parallel Execution Model

- Fine granularity tasks: many more map tasks than machines
- Minimizes time for fault recovery
- Can pipeline shuffling with map execution
- Better dynamic load balancing
- Often use 200,000 map/5000 reduce tasks w/ 2000 machines



Performance

- Typical cluster:
  - 100s/1000s of 2-CPU x86 machines, 2-4 GB of memory
  - Limited bisection bandwidth
  - Storage is on local IDE disks
  - distributed file system manages data (GFS)
  - Job scheduling system: jobs made up of tasks, scheduler assigns tasks to machines



Performance: Locality

- Master scheduling policy:
  - Asks GFS for locations of replicas of input file blocks
  - Map tasks typically split into 64MB (GFS block size)
  - Map tasks scheduled so GFS input block replica are on same machine or same rack
- Effect: Thousands of machines read input at local disk speed
- Without this, rack switches limit read rate

Performance: Replication

- Slow workers significantly lengthen completion time
  - Other jobs consuming resources on machine
  - Bad disks with soft errors transfer data very slowly
  - Weird things: processor caches disabled (!!)
- Solution: Near end of phase, spawn backup copies of tasks
  - Whichever one finishes first "wins"
- Effect: Dramatically shortens job completion time

Performance

- Sorting guarantees within each reduce partition
- Compression of intermediate data
- Combiner: useful for saving network bandwidth

Fault Tolerance

- On worker failure:
  - Detect failure via periodic heartbeats
  - Re-execute completed and in-progress *map* tasks
  - Re-execute in progress *reduce* tasks
  - Task completion committed through master
- Master failure not handled yet
- Robust: lost 1600 of 1800 machines once, but finished fine

Productivity

- User specifies only two functions
- May be complex to specify a general algorithm
- Highly productive for specific kind of problems

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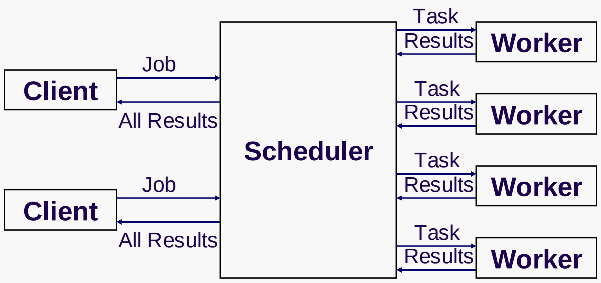
MATLAB DCE

- Executing independent jobs in a cluster environment
- A job is a set of tasks
- A task specifies input data and operations to be performed
- A scheduler takes a job and executes its tasks

Execution Model

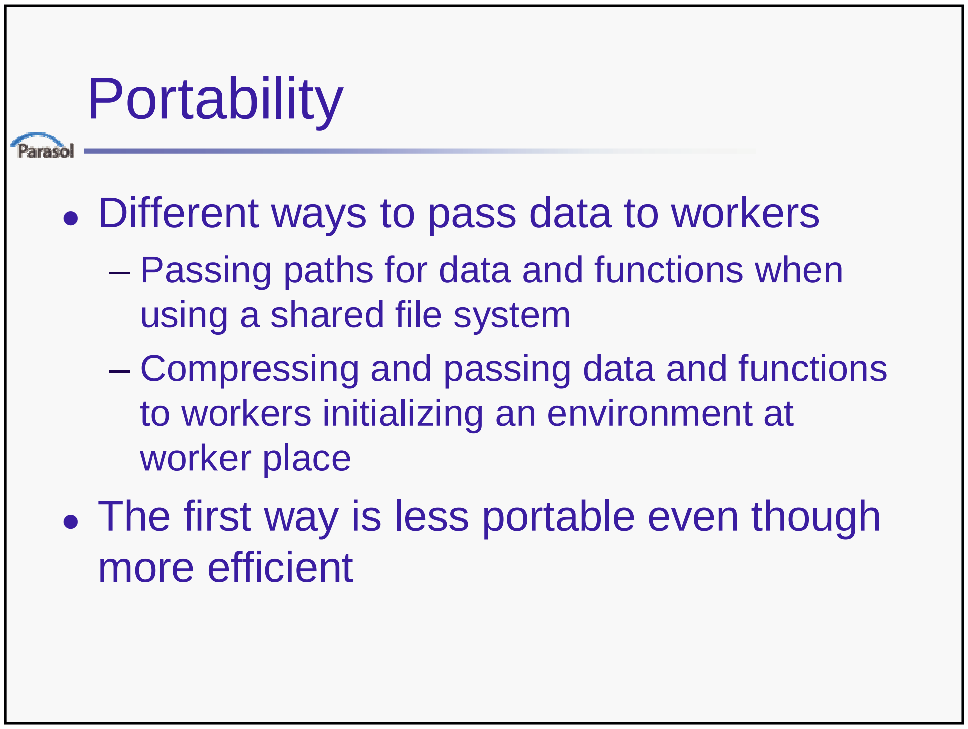


Job Creation and Execution

- Create a Scheduler: `sched = findResource('scheduler', 'type', 'local')`
- Create a Job: `j = createJob(sched);`
- Create Tasks
  - `createTask(j, @sum, 1, {[1 1]});`
  - `createTask(j, @sum, 1, {[2 2]});`
- Submit job: `submit(j);`
- Get results
  - `waitForState(j);`
  - `results = getAllOutputArguments(j)`

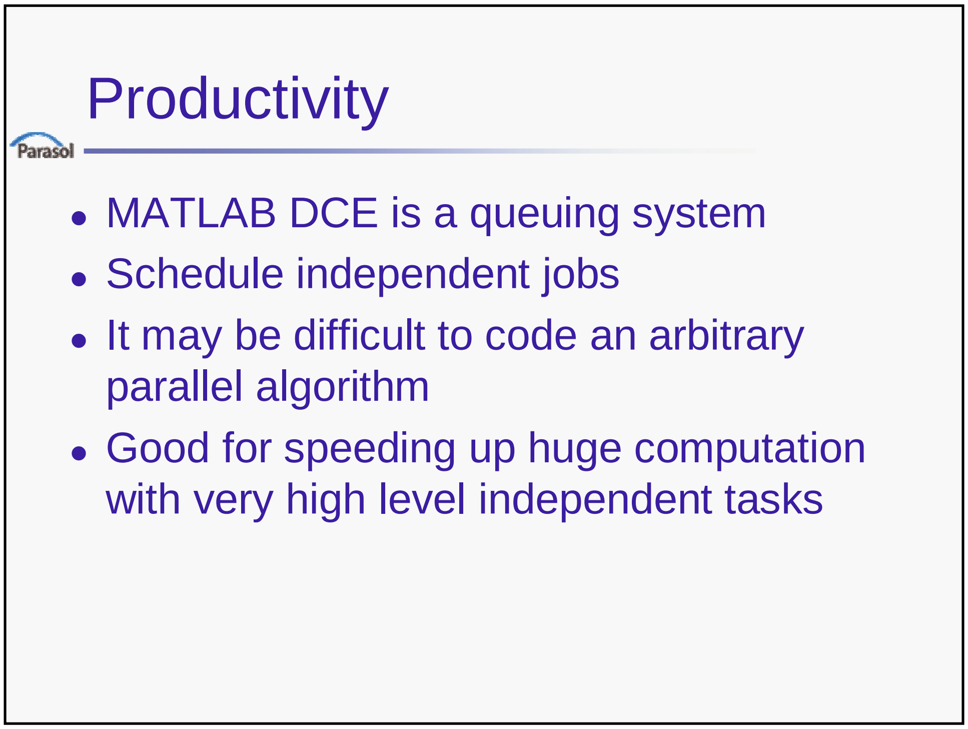
    ```
    results =
    [2]
    [4]
    ```
- Destroy job: `destroy(j);`

Number of output arguments



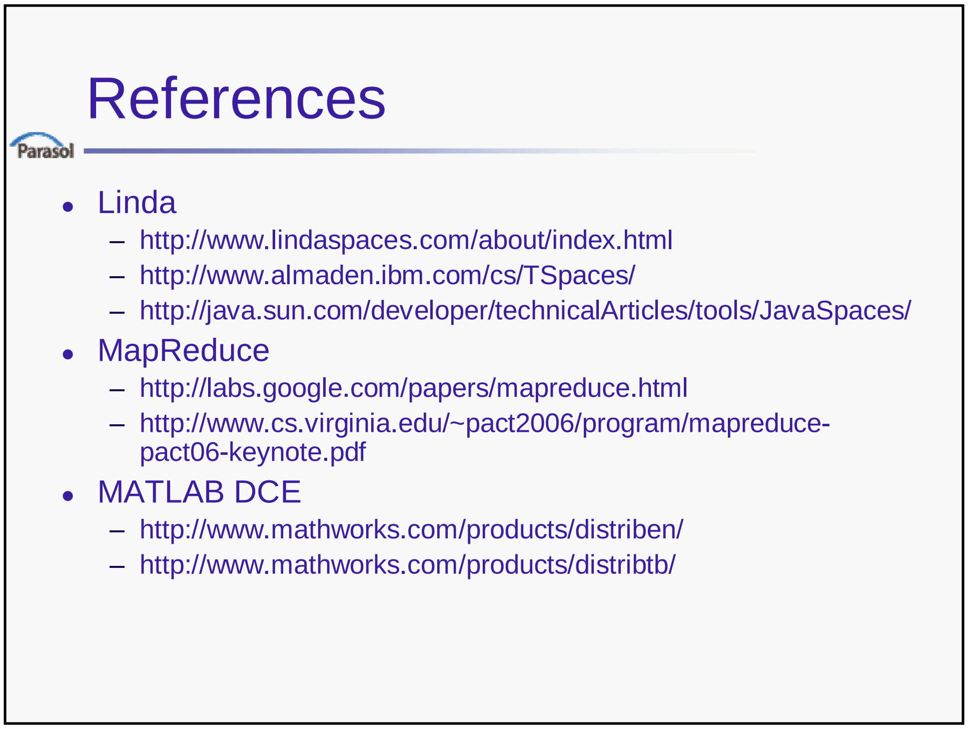
Portability

- Different ways to pass data to workers
  - Passing paths for data and functions when using a shared file system
  - Compressing and passing data and functions to workers initializing an environment at worker place
- The first way is less portable even though more efficient



Productivity

- MATLAB DCE is a queuing system
- Schedule independent jobs
- It may be difficult to code an arbitrary parallel algorithm
- Good for speeding up huge computation with very high level independent tasks



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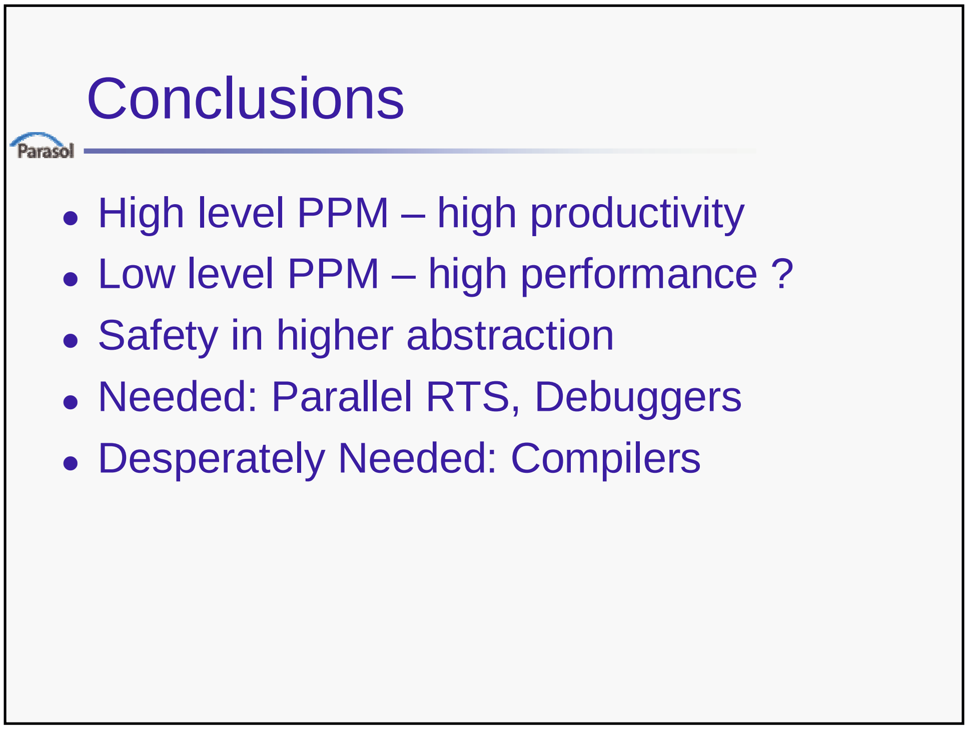

Conclusions

- High level PPM – high productivity
- Low level PPM – high performance ?
- Safety in higher abstraction
- Needed: Parallel RTS, Debuggers
- Desperately Needed: Compilers