George R. Brown School of Engineering
Computer Science

An Introduction to Parallel Programming with Habanero-Java

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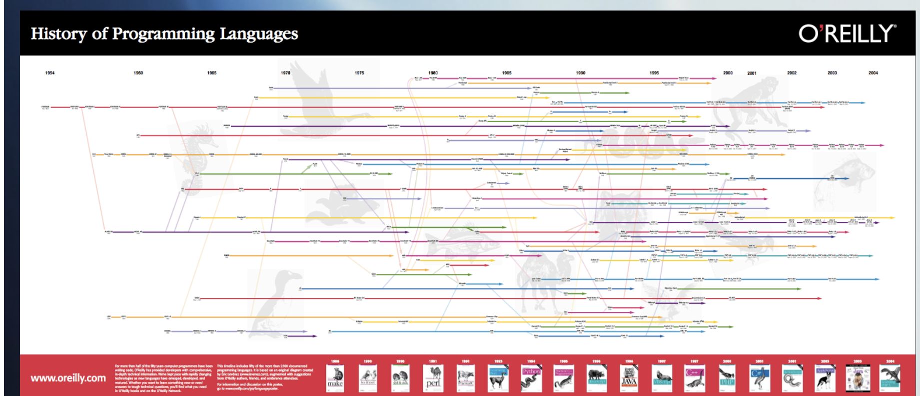
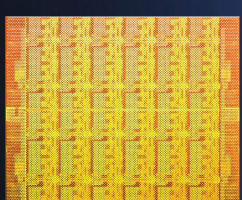
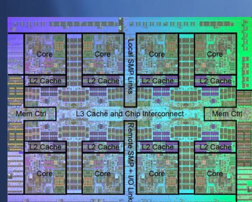
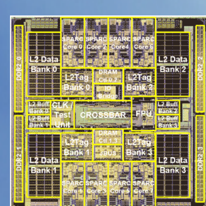
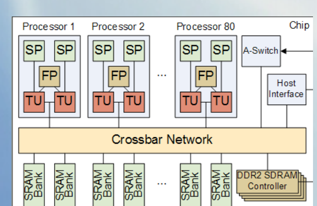
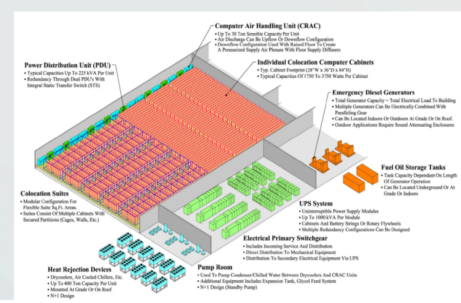




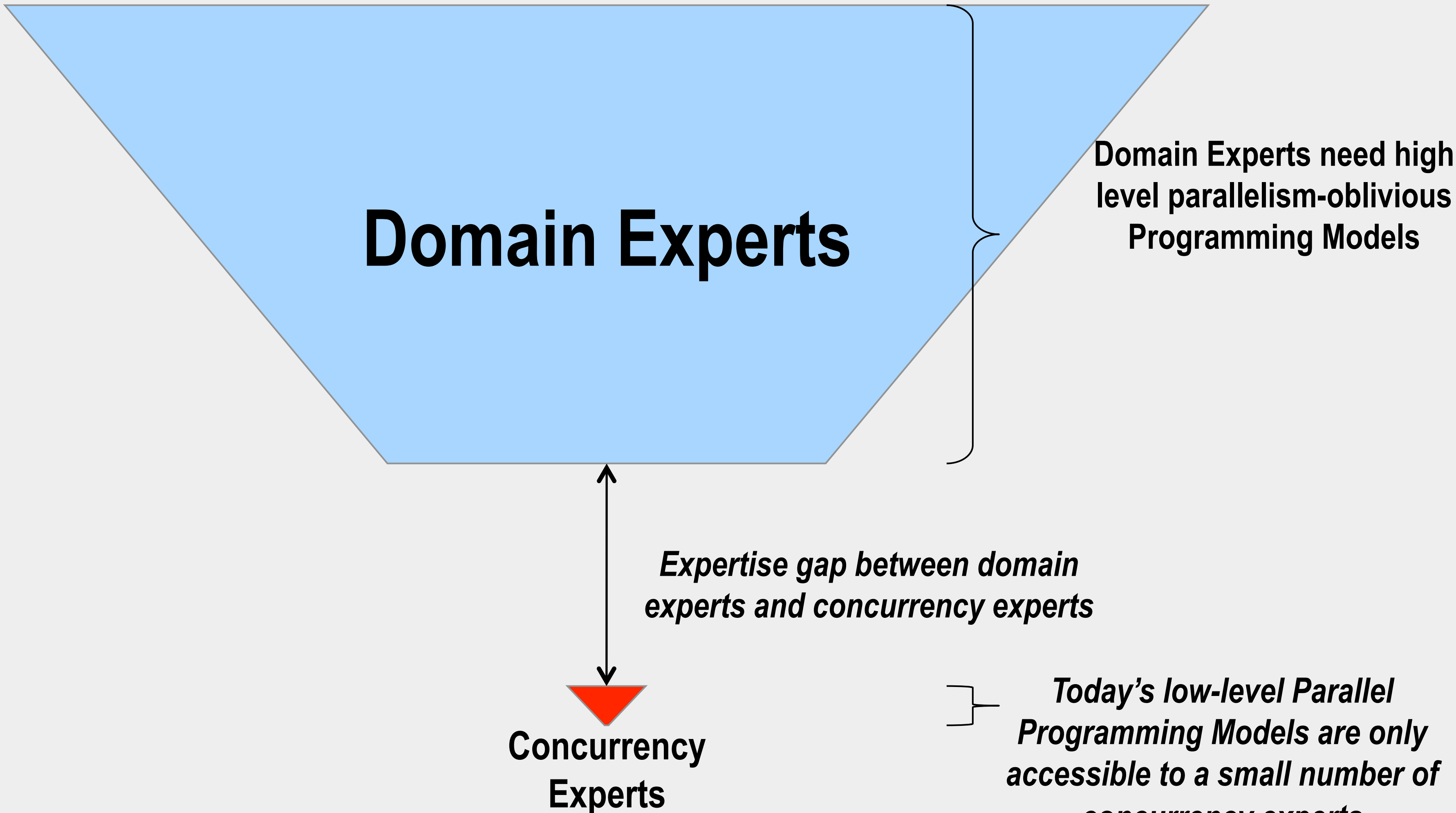




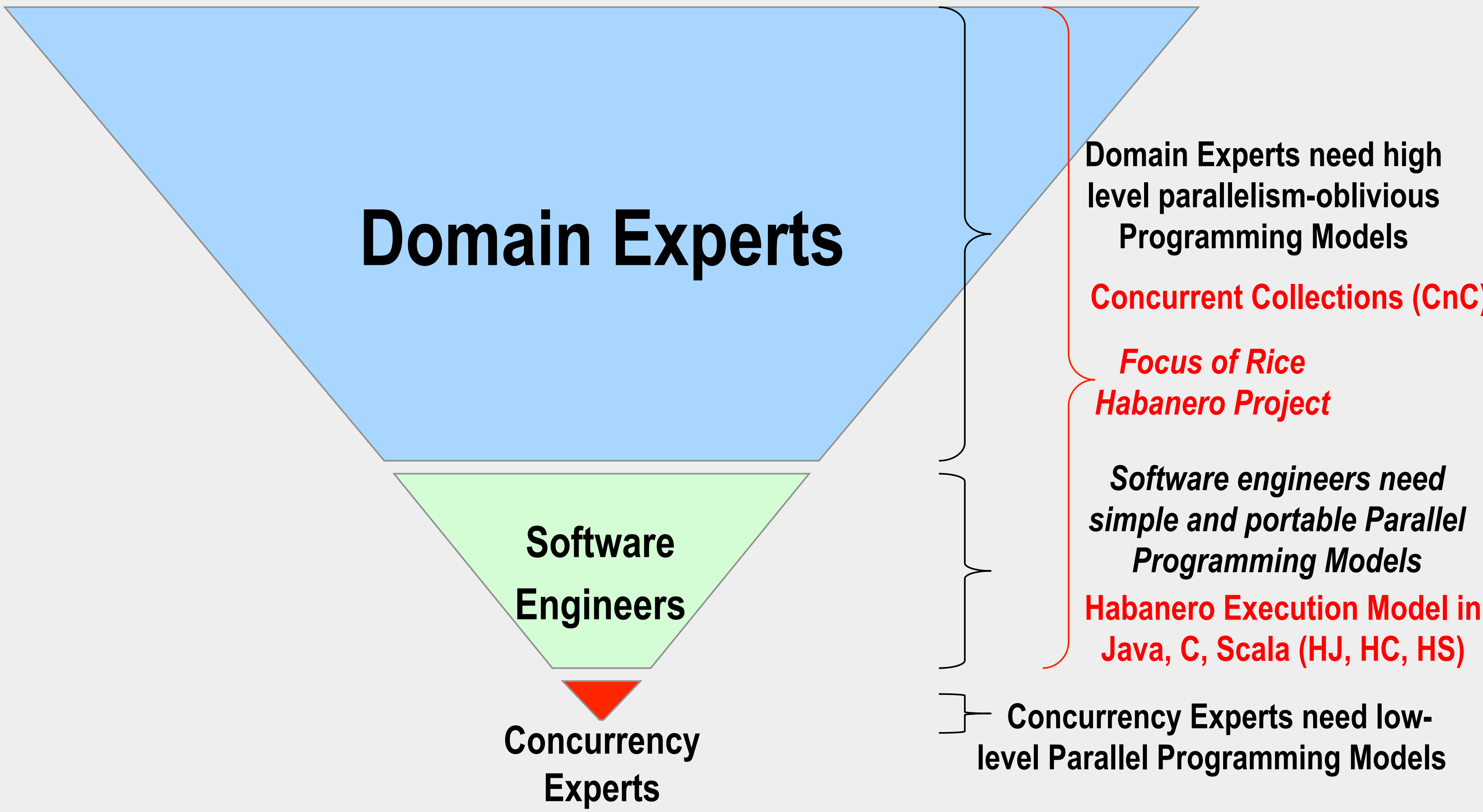




Parallel Software Challenge & Expertise Gap



CS Majors to the Rescue



Habanero-Java (http://habanero.rice.edu/hj)

- New pedagogic language and implementation developed at Rice since 2007
  - Derived from Java-based version of X10 language (v1.5) in 2007
    - X10 language has evolved significantly since then
  - **Habanero-Java (HJ)** is currently an extension of Java 1.4
    - All Java 5 & 6 libraries and classes can be called from HJ programs
    - Front-end support for Java 5 constructs (notably, generics) in progress
    - HJ compiler generates Java classfiles that execute with HJ runtime on a standard JRE
    - Download available at https://wiki.rice.edu/confluence/display/PARPROG/HJDownload
- HJ's parallel extensions are focused on *mid-level* task parallelism
  1. Dynamic task creation & termination: future, async, finish, force, forall, foreach
  2. Mutual exclusion and isolation: isolated
  3. Collective and point-to-point synchronization: phaser, next
  4. Locality control --- task and data distributions: places, here
- **Habanero-C** and **Habanero-Scala** are under development with similar constructs

- Reference: "Habanero-Java: the New Adventures of Old X10". PPPJ 2011, August 2011.

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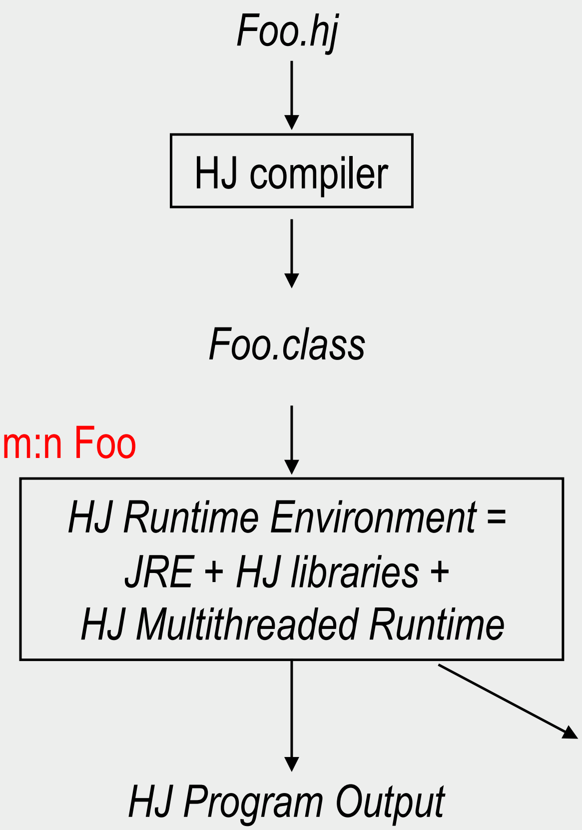
HJ Compilation and Execution Environment



HJ source program --- must contain a class named Foo with a public static void main(String[] args) method

hjc Foo.hj

HJ compiler translates Foo.hj to Foo.class, and inserts calls to HJ runtime as needed

hj –places m:n Foo

HJ runtime allocates m*n worker threads across m "places" (default values: m = 1, n = 3)

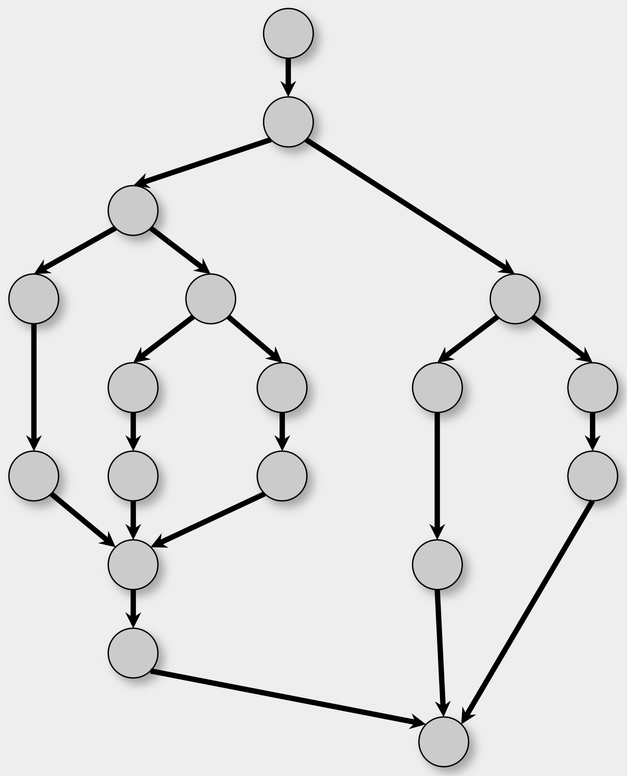
HJ Abstract Performance Metrics
(optional, enabled by –perf=true *option for hj command)*

COMP 322: Fundamentals of Parallel Programming

- **Sophomore-level CS Course at Rice**
  - https://wiki.rice.edu/confluence/display/PARPROG/COMP322
  - Or do a web search on "comp322 wiki"
- **Approach**
  - **Mid-level parallel programming --- "Simple things should be simple, complex things should be possible"**
  - Introduce students to fundamentals of parallel programming
    - Primitive constructs for task creation & termination, collective & point-to-point synchronization, task and data distribution, and data parallelism
    - Abstract models of parallel computations and computation graphs
    - Parallel algorithms & data structures including lists, trees, graphs, matrices
    - Common parallel programming patterns
  - Use Habanero-Java (HJ) as pedagogical language for two-thirds of course, and then teach standard programming models (Java threads, MPI, CUDA) using HJ principles

Algorithmic Complexity Measures

T_P = execution time on P processors



$PROC_0$ . . . $PROC_{P-1}$

Computation graph abstraction:

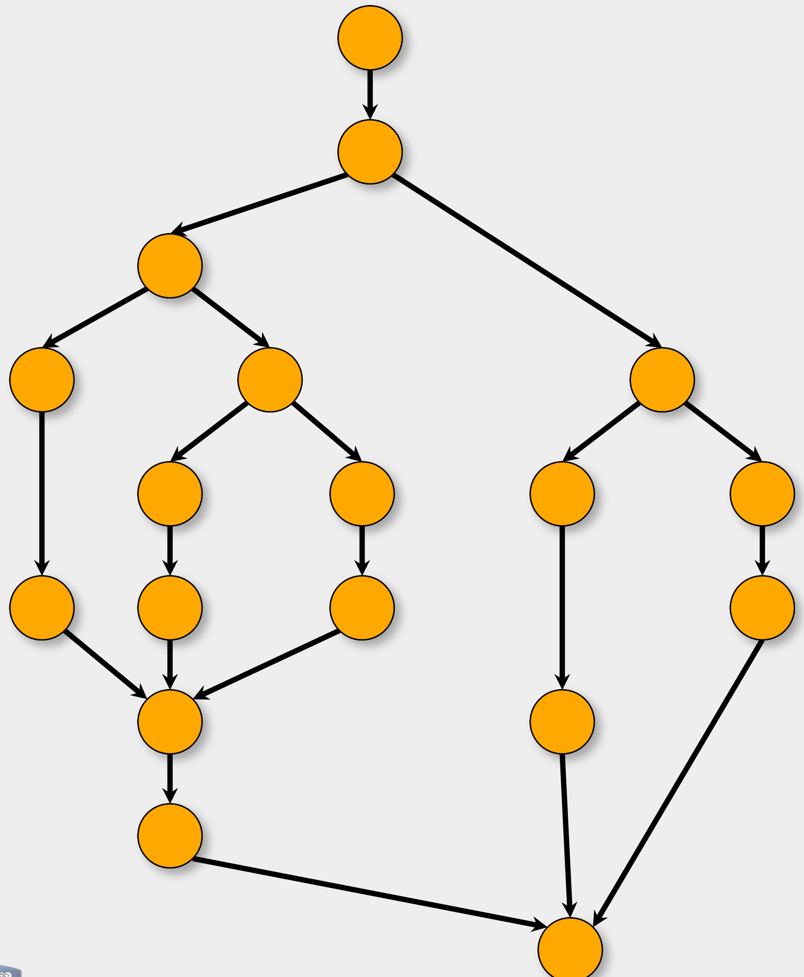
- *Node = arbitrary sequential computation*
- *Edge = dependence (successor node can only execute after predecessor node has completed)*
- *Directed acyclic graph (dag)*

Processor abstraction:

- *P identical processors*
- *Each processor executes one node at a time*

Algorithmic Complexity Measures

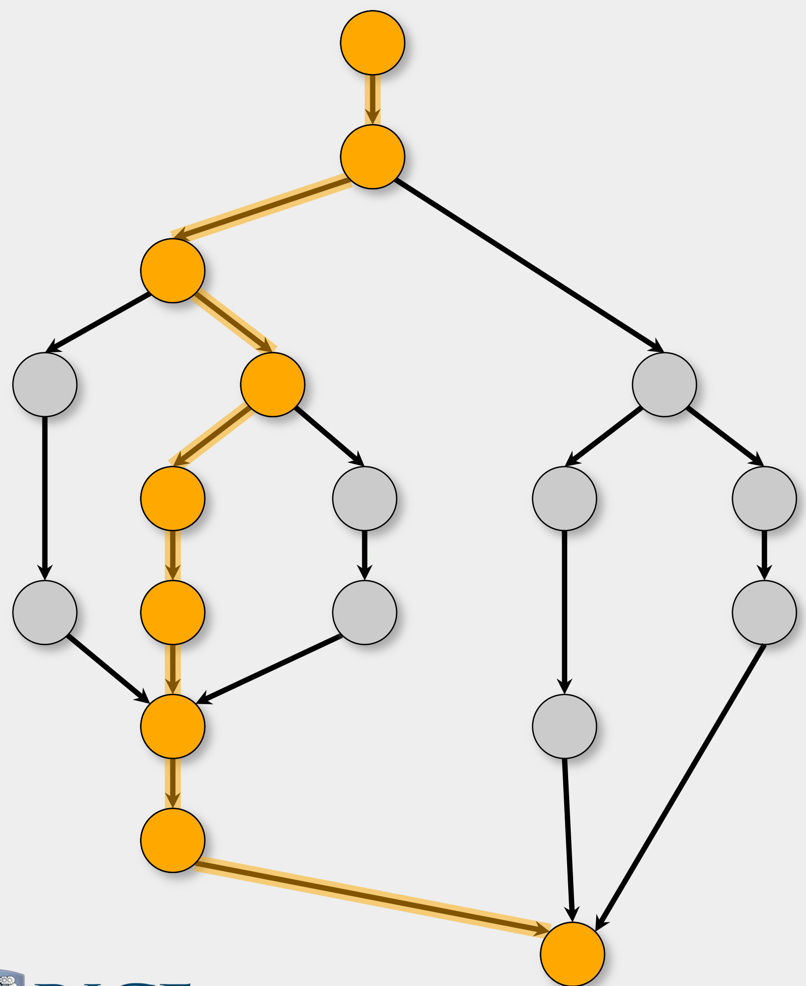
T_P = execution time on P processors



T_1 = *work*

Algorithmic Complexity Measures

T_P = execution time on P processors



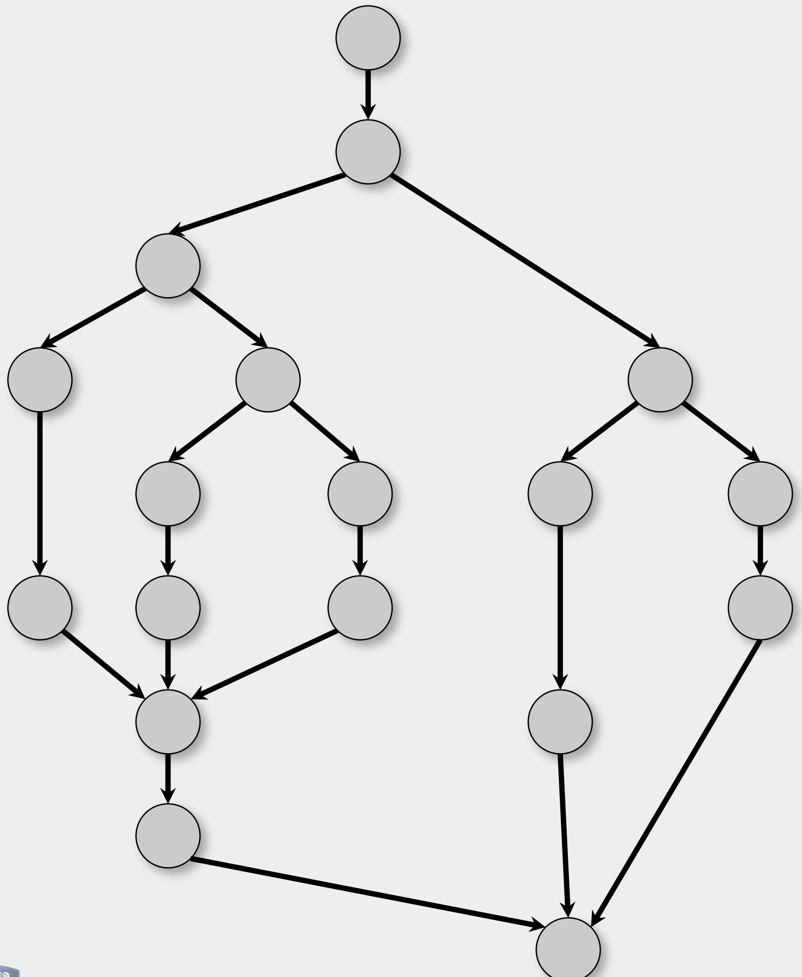
T_1 = *work*

T_∞ = *span**

*Also called *critical-path length* or *computational depth*.

Algorithmic Complexity Measures

T_P = execution time on P processors



T_1 = *work*

T_∞ = *span*

LOWER BOUNDS

$T_P \geq T_1/P$

$T_P \geq T_\infty$

T_1/T_P = *speedup* on P processors

Parallelism ("Ideal Speedup")

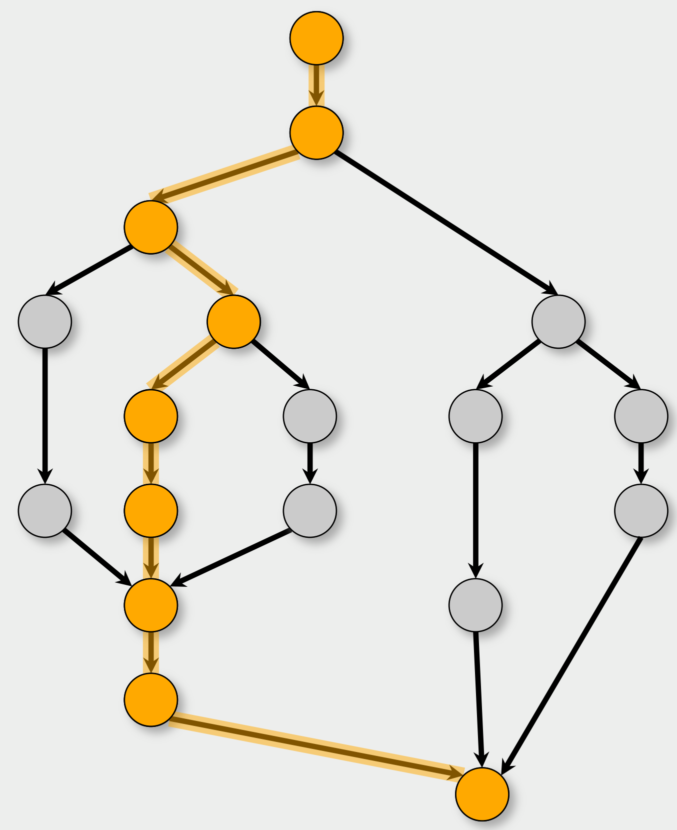
T_P depends on the schedule of computation graph nodes on the processors

➔ Two different schedules can yield different values of T_P for the same P

For convenience, define *parallelism* (or ideal speedup) as the ratio T_1/T_∞

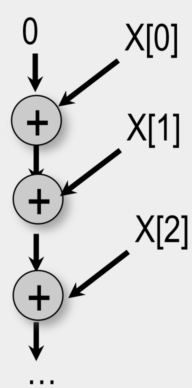
Parallelism is independent of P, and only depends on the computation graph

Also define *parallel slackness* as the ratio, $(T_1/T_\infty)/P$



Example 1: Array Sum (sequential version)

- Problem: compute the sum of the elements X[0] … X [n-1] of array X
- Sequential algorithm
  - sum = 0; for (i=0 ; i< n ; i++) sum += X[i];
- Computation graph



Example 1: Array Sum (parallel iterative version)

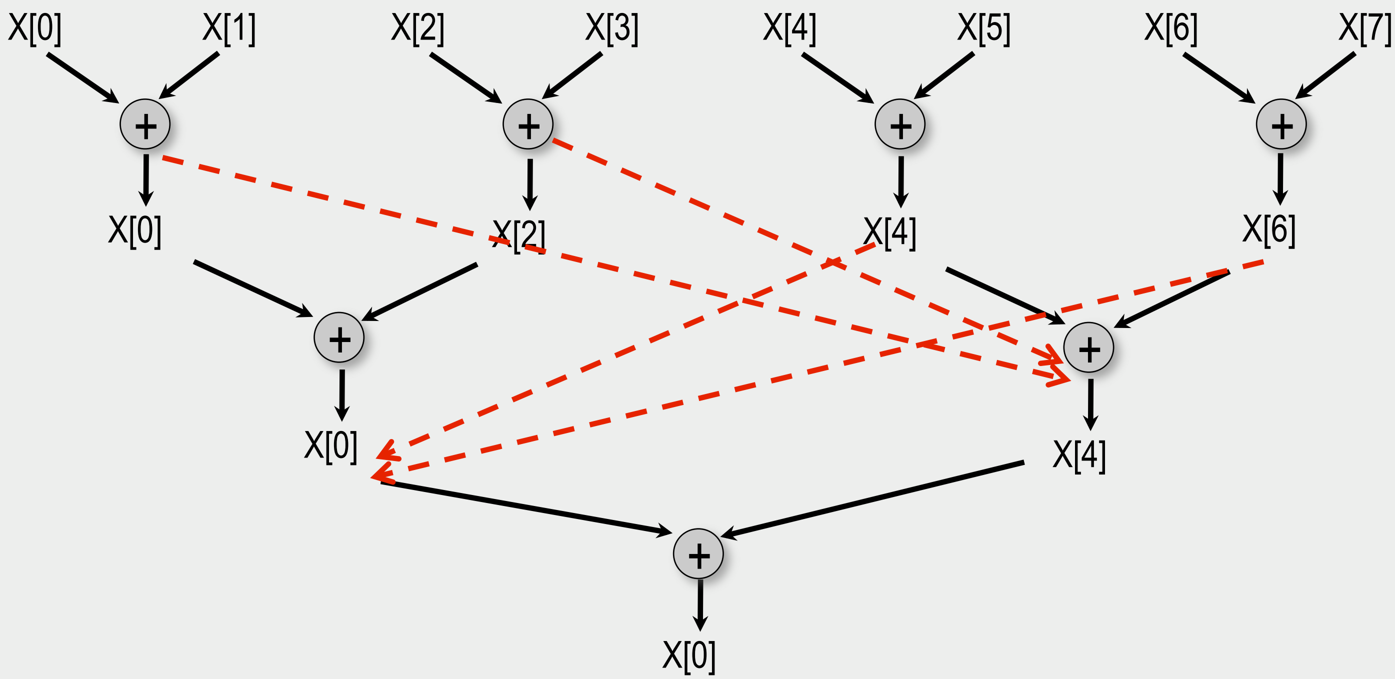
- Parallel algorithm (iterative version, assumes n is a power of 2)

```
for ( step = 1; step < n ; step *= 2 ) { // iterates for lg n steps
    size = n / (2*step);    // number of adds to be performed in current step
    forall ( point [i] : [0:size-1] ) X[2*i*step] += X[(2*i+1)*step];
}
sum = X[0];
```

- HJ forall construct executes all iterations in parallel
  - forall body can read (but not write) outer local variables (copied on entry)
- This algorithm overwrites X (make a copy if X is needed later)
- Work = O(n), Span = O(log n), Parallelism = O(n / (log n))
- NOTE: this and the next parallel algorithm can be used for any associative operation on array elements (need not be commutative) e.g., multiplication of an array of matrices

Example 1: Array Sum (parallel iterative version)

Computation graph for n = 8



- - -> Extra orderings due to forall construct

Example 1: Array Sum (parallel recursive version)

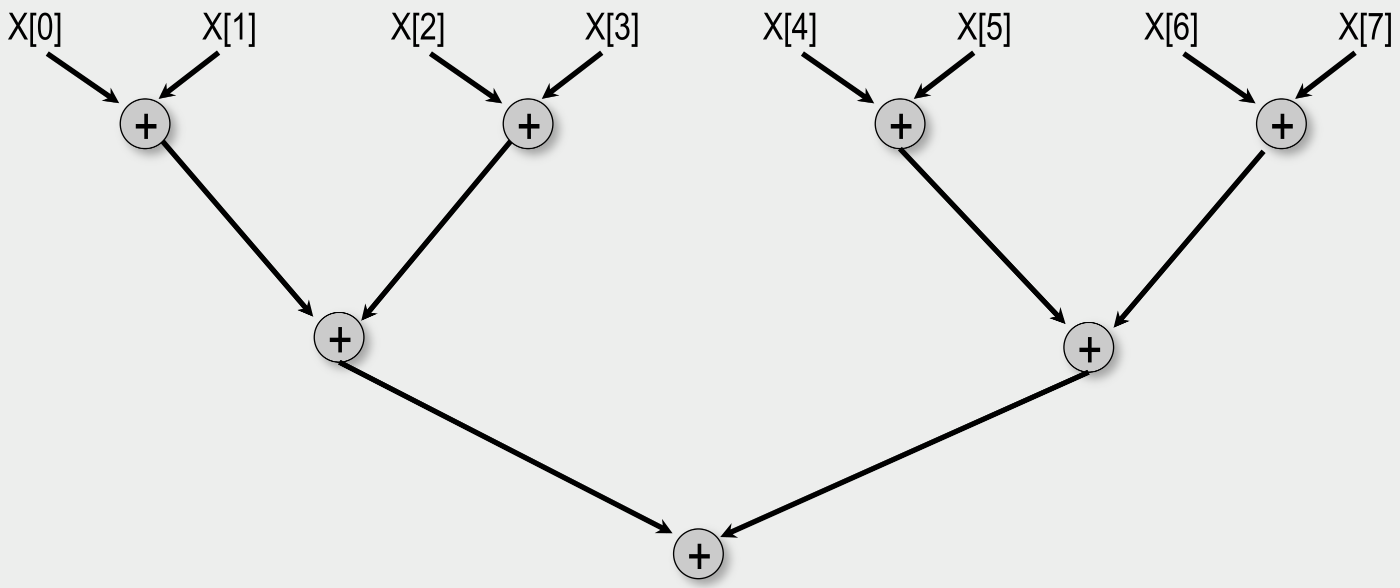
- Parallel algorithm (recursive version, assumes n is a power of 2)

```
sum = computeSum(X, 0, n-1);
int computeSum(final int[] X, final int lo, final int hi) {
    if ( lo > hi ) return 0;
    else if ( lo == hi ) return X[lo];
    else {
        int mid = (lo+hi)/2;
        final future<int> sum1 = async<int> { return computeSum(X, lo, mid); }
        final future<int> sum2 = async<int> { return computeSum(X, mid+1, hi); }
        return sum1.get() + sum2.get();
    }
} // computeSum
```

- "future" executes child expression in parallel with parent
  - get() causes the parent to wait for the child.

Example 1: Array Sum (parallel recursive version)

Computation graph for n = 8



Work = O(n), Span = O(log n), Parallelism = O(n / (log n))

No extra orderings as in forall case

Four classes of mid-Level Parallel Constructs

1) <u>Asynchronous tasks and data transfers</u> e.g.,

- MPI: *mpi_isend, mpi_irecv, mpi_wait*
- OpenMP: *task, taskwait*
- Cilk: *spawn, sync*
- CAF, UPC, Chapel: *function shipping*
- X10: *async, finish*
- **Habanero: *async, finish, asyncMemcpy, futures, foreach, forall, async-await***

2) <u>Collective and point-to-point synchronization & reductions</u> e.g.,

- MPI: *mpi_send, mpi_recv*, *mpi_barrier, mpi_reduce,*
- OpenMP: *barrier, reductions*
- Cilk: *reducers*
- CAF, UPC, Chapel: *barrier, reductions*
- X10: *clocks, finish accumulators, conditional atomic*
- **Habanero: *phasers, phaser accumulators, finish accumulators***

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Four classes of mid-Level Parallel Constructs

3) <u>Mutual exclusion</u> e.g.,

- OpenMP: *atomic, critical*
- X10, Chapel, STM systems: *atomic*
- Galois: operations on unordered sets
- **Habanero: *isolated (weak atomicity)***

4) <u>Locality control for task and data distribution</u> e.g.,

- MPI: *all-local (shared-nothing)*
- CAF, Chapel, UPC, X10: *PGAS storage model (local vs. remote)*
- Sequoia: *hierarchical storage model w/ static tasks*
- **Habanero: *hierarchical place tree w/ dynamic parallelism, heterogeneity***

- Scalable implementations of these constructs require first-class compiler and runtime support
- Constructs can be used to raise current low-level programming models, or as target for high-level programming models

Rice Habanero Multicore Software Project: Enabling Technologies for Extreme Scale

Parallel Applications

Portable execution model

1) Lightweight asynchronous tasks and data transfers
- *async, finish, asyncMemcpy*

2) Locality control for task and data distribution
- *hierarchical place tree*

3) Mutual exclusion
- *isolated*

4) Collective and point-to-point synchronization
- *phasers*

Habanero Programming Languages

Habanero Static Compiler & Parallel Intermediate Representation

Habanero Runtime System

Two-level programming model

Declarative Coordination Language for Domain Experts, CnC (Intel Concurrent Collections)

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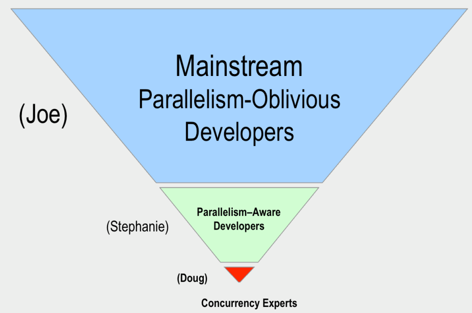
Task-Parallel Languages for Parallelism-aware Developers: Habanero-Java (from X10 v1.5), Habanero-C, Habanero-Scala



Extreme Scale Platforms

http://habanero.rice.edu

HJ Futures: Functional Tasks with Return Values

async<T> { <Stmt-Block> }

- Creates a new child task that executes Stmt-Block, which must terminate with a return statement returning a value of type T
- Async expression returns a reference to a *container* of type future<T>, and parent task can proceed immediately to operation following the async
- Values of type future<T> can only be assigned to *final variables*

Expr.get()

- Evaluates Expr, and blocks if Expr's value is unavailable
- Expr must be of type future<T>
- Return value from Expr.get() will then be T
- *Assignment of future references to final variables guarantees deadlock freedom with get() operations*

HJ Async and Finish: Imperative Tasks

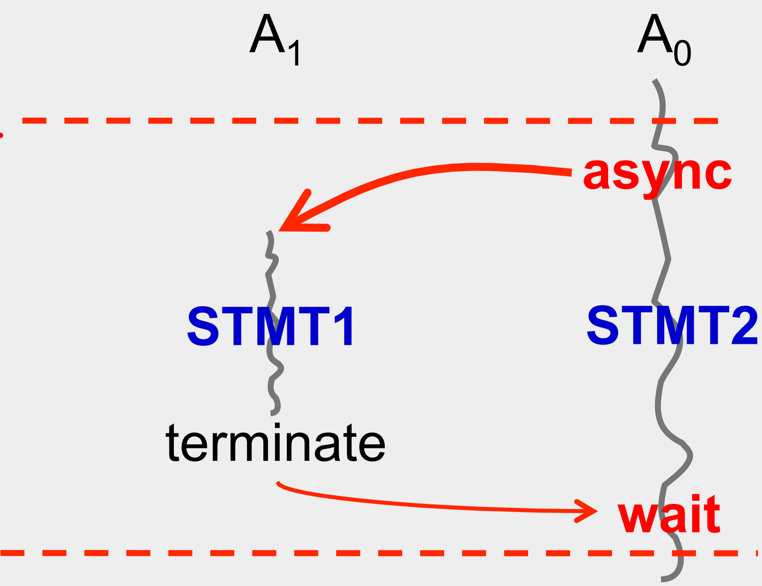
async [seq(cond)] S

- Creates a new child task that executes statement S ; parent task can proceed immediately to operation following the async
- Optional “seq” clause
  - async seq(cond) <stmt> ≡
    if (cond) <stmt> else async <stmt>

finish S

- Execute S, but wait until *all* (transitively) spawned asyncs in S‘s scope have terminated.
- Implicit finish between start and end of main program
- *Use of finish synchronization cannot create a deadlock cycle*

```
//A0(Parent)
finish {    //Begin finish
  async {
    STMT1; //A1(Child)
  }
  STMT2;    //A0
}           //End finish
```



Task Creation: Library Approach

```
List<Callable<Void>> list = …
for(int i = …) {
  list.add(new Callable<Void>() {
    public Void call() {
     // some computation
    }
   });
}
executor.invokeAll(list);
```

- What do we need ?
  - A task executor
  - A task interface
  - A task implementation
- Drawback
  - Readability
  - Programming chores
    - Manage tasks
    - Schedule tasks
  - Error-prone!

Task Creation: Language Approach

```
finish {
  for(int i = …) {
        async {
         // some computation
        }
  }
}
```

- What a mainstream programmer wants ?
- Run "this statement in parallel
  - Simple task creation
  - No task management
  - No explicit task scheduling

HJ isolated statement

isolated <body>

- Two tasks executing isolated statements with interfering accesses must perform the isolated statement in mutual exclusion
  - Two instances of isolated statements, ⟨stmt1⟩ and ⟨stmt2⟩, are said to interfere with each other if both access a shared location, such that at least one of the accesses is a write.

  ➔ Weak atomicity guarantee: no mutual exclusion applies to non-isolated statements i.e., to (isolated, non-isolated) and (non-isolated, non-isolated) pairs of statement instances
- Isolated statements may be nested (redundant)
- Isolated statements must not contain any other parallel statement: async, finish, get, forall
- In case of exception, all updates performed by <body> before throwing the exception will be observable after exiting <body>

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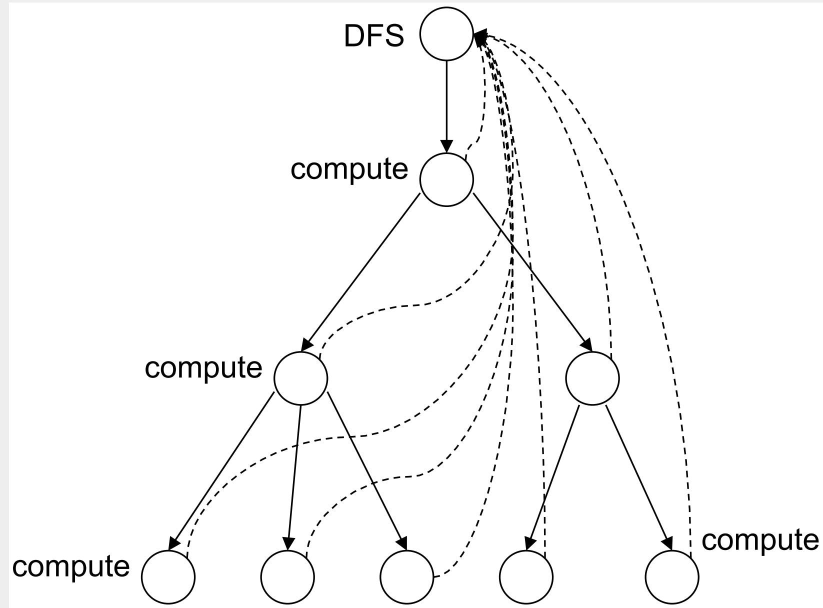
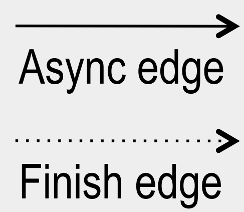
Parallel Spanning Tree Algorithm using Finish, Async, and Isolated constructs

```
class V  {
  V [] neighbors; // Input adjacency list
  V parent; // Output spanning tree
  . . .
  boolean tryLabeling(V n) {
    isolated if (parent == null) parent = n;
    return parent == n;
  } // tryLabeling
  void compute() {
    for (int i=0; i<neighbors.length; i++) {
      V child = neighbors[i];
      if (child.tryLabeling(this))
          async child.compute(); //escaping async
     }
  } // compute
} // class V

root.parent = root; //Use self-cycle to identify root
finish root.compute();
```





Computation Graphs for HJ Programs

- A Computation Graph (CG) is an abstract data structure that captures the dynamic execution of an HJ program
- The nodes in the CG are *steps* in the program's execution
    - A step is a sequential subcomputation of a task that contains no continuation points
    - When a worker starts executing a step, it can execute the entire step without interruption
    - Steps need not be maximal i.e., it is acceptable to split a step into smaller steps if so desired

Example HJ Program Decomposed into Non-Maximal Steps (v1 … v23)

```
// Task T1
v1; v2;
finish {
 async {
  // Task T2
  v3;
  finish {
   async { v4; v5; } // Task T3
   v6;
   async { v7; v8; } // Task T4
   v9;
  } // finish
  v10; v11;
```

```
// Task T2 (contd)
  async { v12; v13;
        v14; } // Task T5
  v15;
 } // end of task T2
 v16; v17; // back in Task T1
} // finish
v18; v19;
finish {
 async {
  // Task T6
  v20; v21; v22; }
}
v23;
```

Computation Graph Edges

- CG edges represent ordering constraints
- There are three kinds of CG edges of interest in an HJ program with finish &async operations
  1. *Continue* edges define sequencing of steps within a task
  2. *Spawn* edges connect parent tasks to child async tasks
  3. *Join* edges connect async tasks to their Immediately Enclosing Finish (IEF) operations

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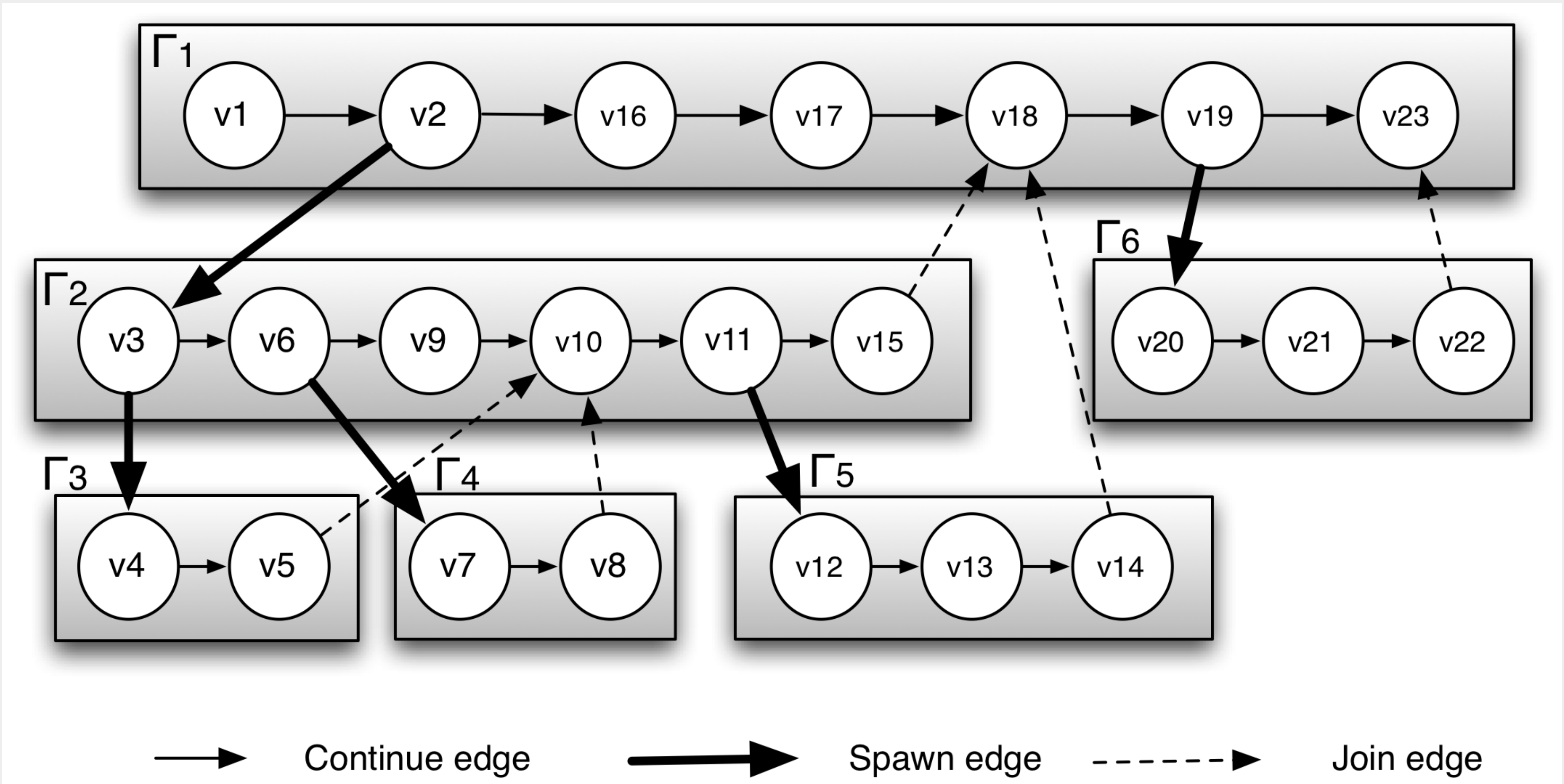
Computation Graph for previous HJ Example



Observation: Step v16 can potentially execute in parallel with steps v3 … v15

Dependences in a Computation Graph

- Given edge (A,B) in a CG, node B can only start execution after node A has completed
- We say that *node Y depends on node X* if there is a path of directed edges from X to Y in the CG
  - Also referred to as a “dependence from node X to node Y” or a “dependence from node Y on node X”
- Nodes X and Y can *potentially execute in parallel* if there is no dependence from X to Y or from Y to X
- Dependence is a *transitive* relation
  - if B depends on A and C depends on B, then C must depend on A
- All computation graphs must be acyclic
  - It is not possible for a node to depend on itself
- Computation graphs are examples of *directed acyclic graphs* (dags)

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Complexity Measures for Computation Graphs

Define

- time(N) = execution time of node N
- WORK(G) = sum of time(N), for all nodes N in CG G
  - WORK(G) is the total amount of work to be performed in G
- CPL(G) = length of a longest path in CG G, when adding up the execution times of all nodes in the path
  - Such paths are called *critical paths*
  - CPL(G) is the length of these paths (*critical path length*)

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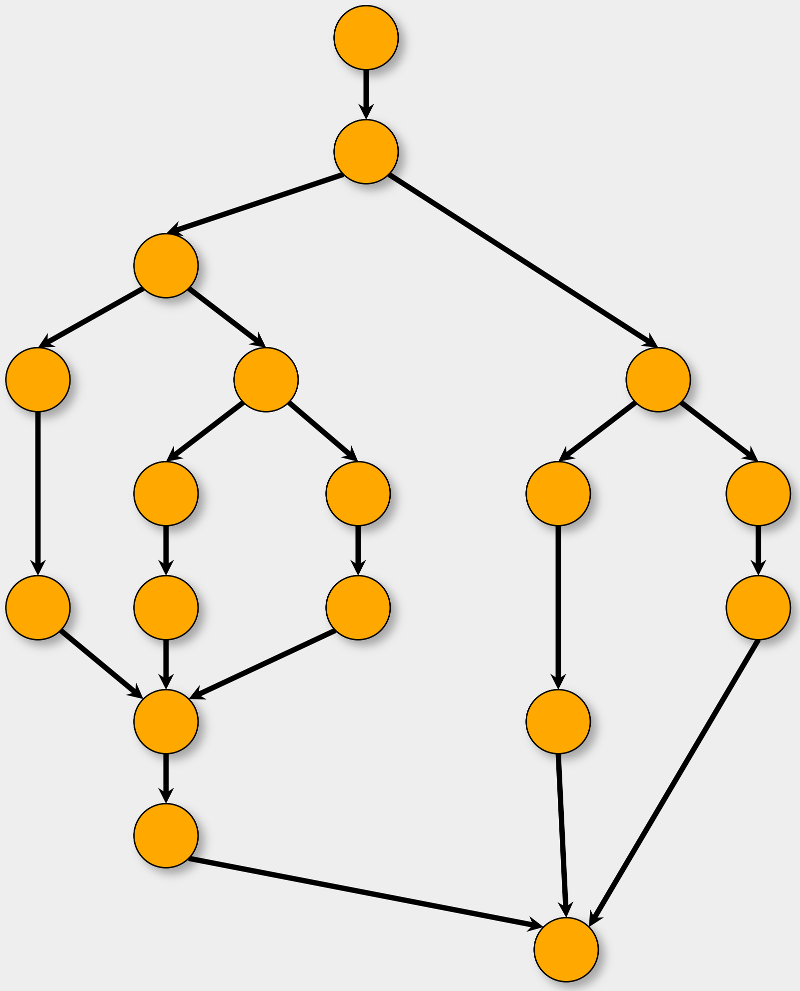
Example

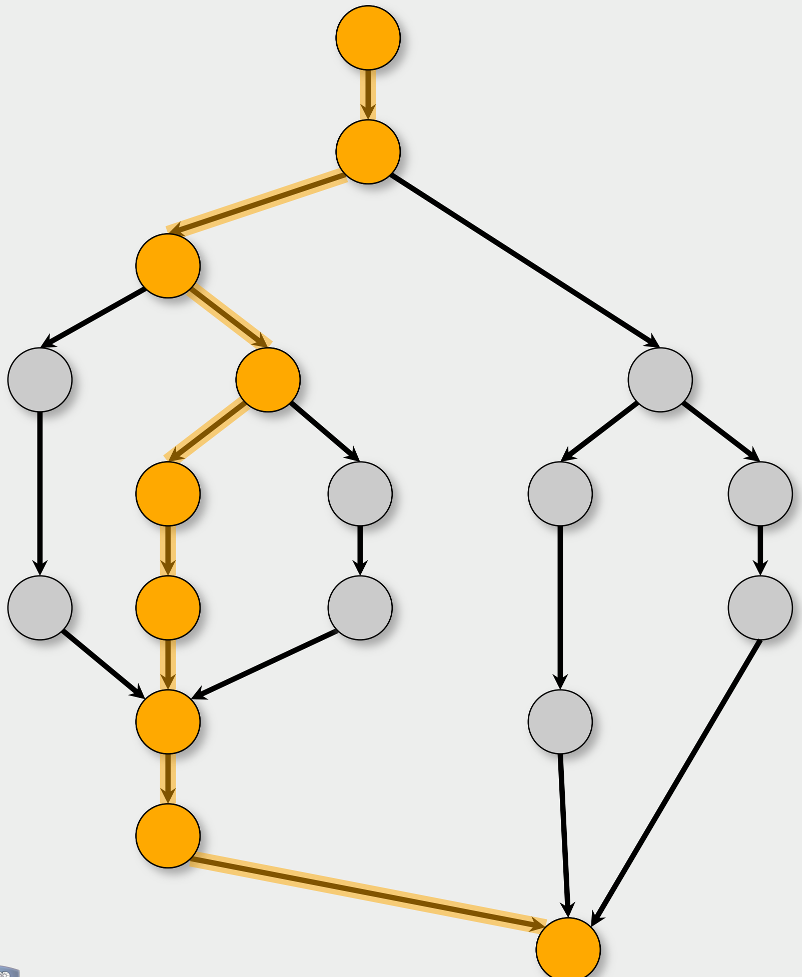
Assume time(N) = 1 for all nodes in this graph



WORK(G) = 18

Example (contd)

Assume time(N) = 1 for all nodes in this graph



CPL(G) = 9

Lower Bounds on Execution Time

- t_P = execution time of computation graph on P processors
- Observations
  - t_1 = WORK(G)
  - t_∞ = CPL(G)
- Lower bounds
  - Capacity bound: $t_P \geq WORK(G)/P$
  - Critical path bound: $t_P \geq$ CPL(G)
- Putting it together
  - $t_P \geq \max(WORK(G)/P, CPL(G))$

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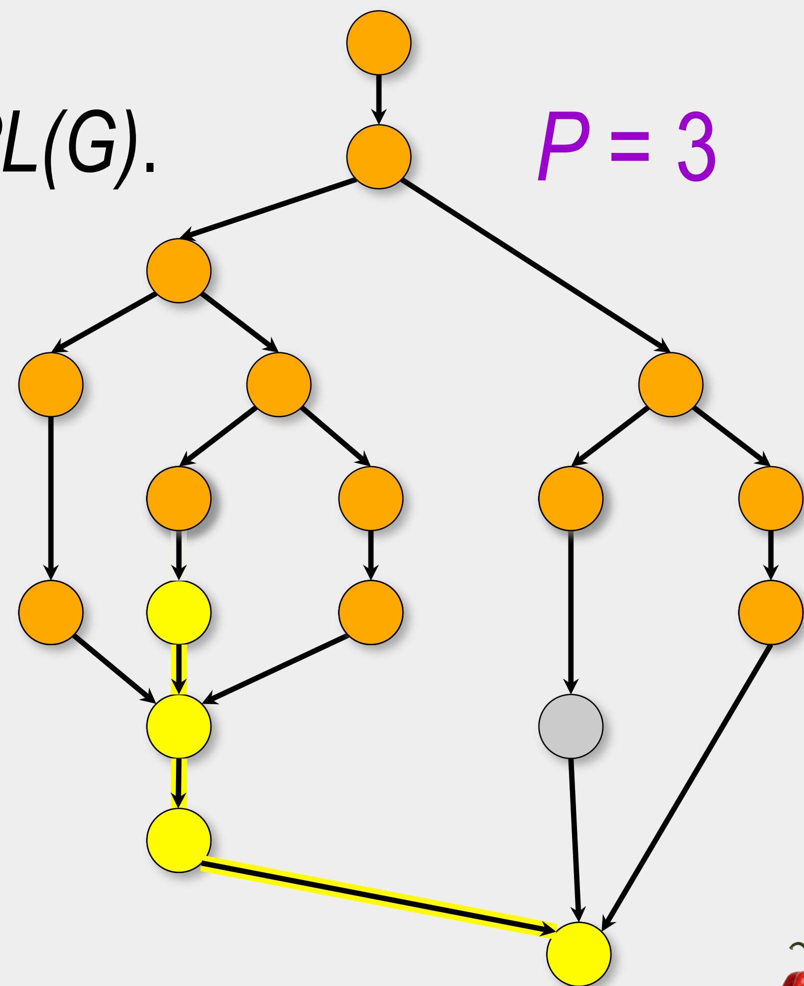
Greedy-Scheduling Theorem (Upper Bound)

Theorem [Graham '66]. Any greedy scheduler achieves

$$t_P \leq WORK(G)/P + CPL(G).$$

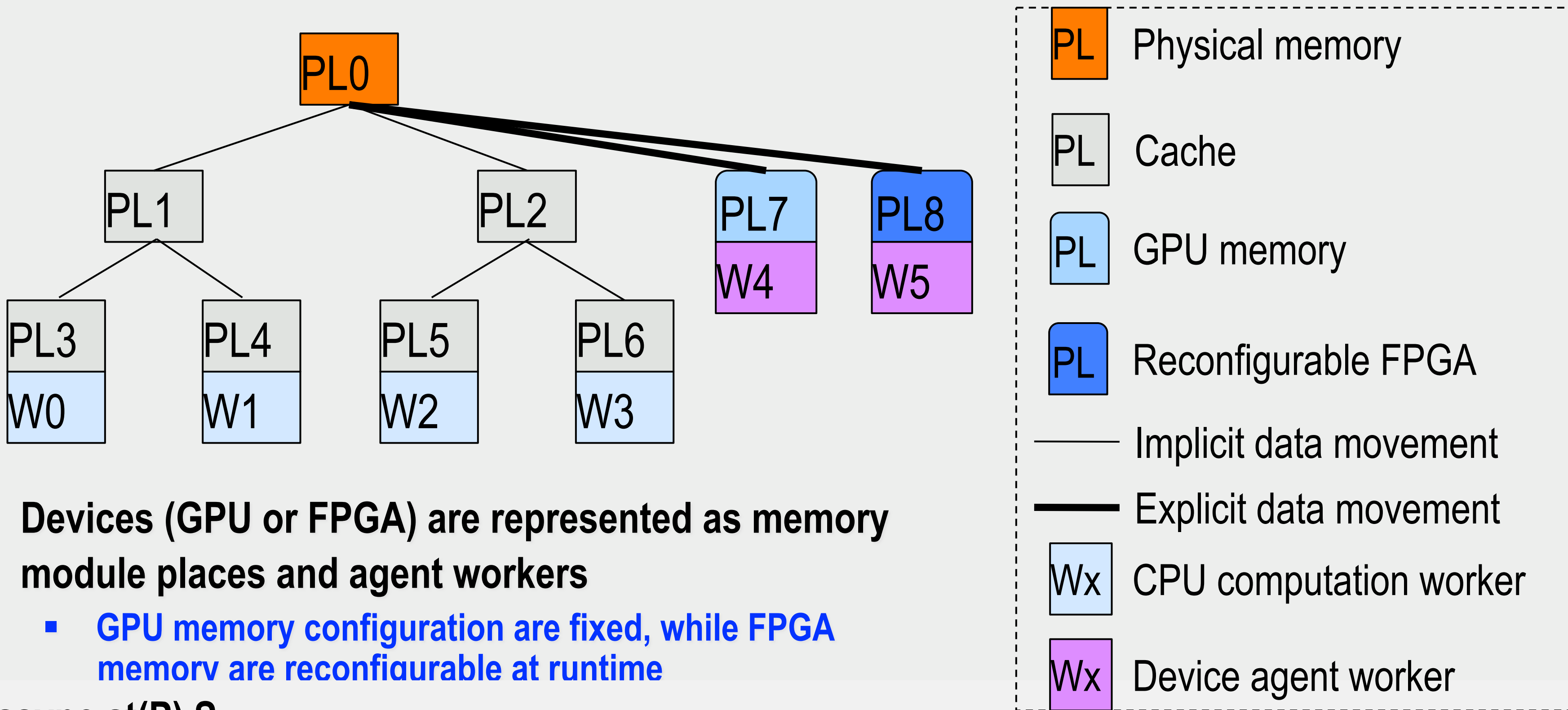


Proof sketch.

complete steps ≤ *WORK(G)/P*, since each complete step performs *P* work.

incomplete steps ≤ *CPL(G)*, since each incomplete step reduces the span of the unexecuted dag by 1. ■

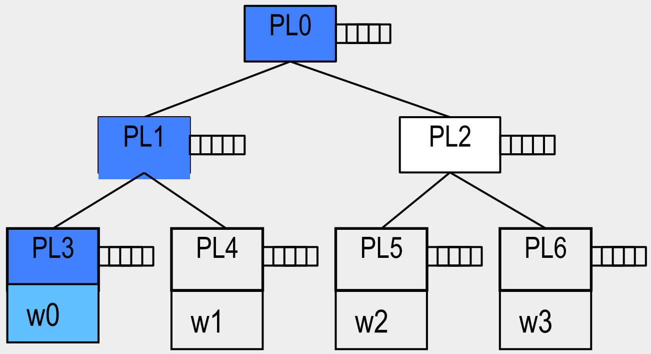
Hierarchical Place Trees for Locality and Heterogeneity



- **Devices (GPU or FPGA) are represented as memory module places and agent workers**
  - **GPU memory configuration are fixed, while FPGA memory are reconfigurable at runtime**
- **async at(P) S**
  - **Creates new activity to execute statement S at place P**
- **Physically explicit data transfer between main memory and device memory**
  - **Use of IN and OUT clauses to improve programmability of data transfers**
- **Device agent workers**
  - **Perform asynchronous data copy and task launching for device**

Locality-aware Scheduling using the HPT

- Workers attached to leaf places
  - Bind to hardware core
- Each place has a queue
  - async <*pl*> <*stmt*>: push task onto *pl*'s queue



- A worker executes tasks from ancestor places from bottom-up
  - W0 executes tasks from PL3, PL1, PL0
- Tasks in a place queue can be executed by all workers in the place's subtree
  - Task in PL2 can be executed by workers W2 or W3

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Logical Structure of a CUDA kernel invocation in HJ terms

```
finish async at(GPU) {
  // Parallel execution of blocks in grid
  forall (point[blockIdx.x, blockIdx.y] : [0:gridDim.x-1,0:gridDim.y-1]) {
    // Parallel execution of threads in block (blockIdx.x, blockIdx.y)
    forall (point[threadIdx.x, threadIdx.y, threadIdx.z]
                  : [0:blockDim.x-1,0:blockDim.y-1,0:blockDim.z-1]) {
      // Perform kernel computation as function of blockIdx.x, blockIdx.y
      // and threadIdx.x, threadIdx.y, threadIdx.z
      . . .
      next; // barrier synchronizes inner forall only (__syncthreads)
      . . .
    } // forall threadIdx.x, threadIdx.y, threadIdx.z
  } // forall blockIdx.x, blockIdx.y
} // finish async (GPU)
```

Listing 1: Logical structure of a CUDA kernel invocation

- Future work: automatic generation of CUDA/ OpenCL from above HJ code structure

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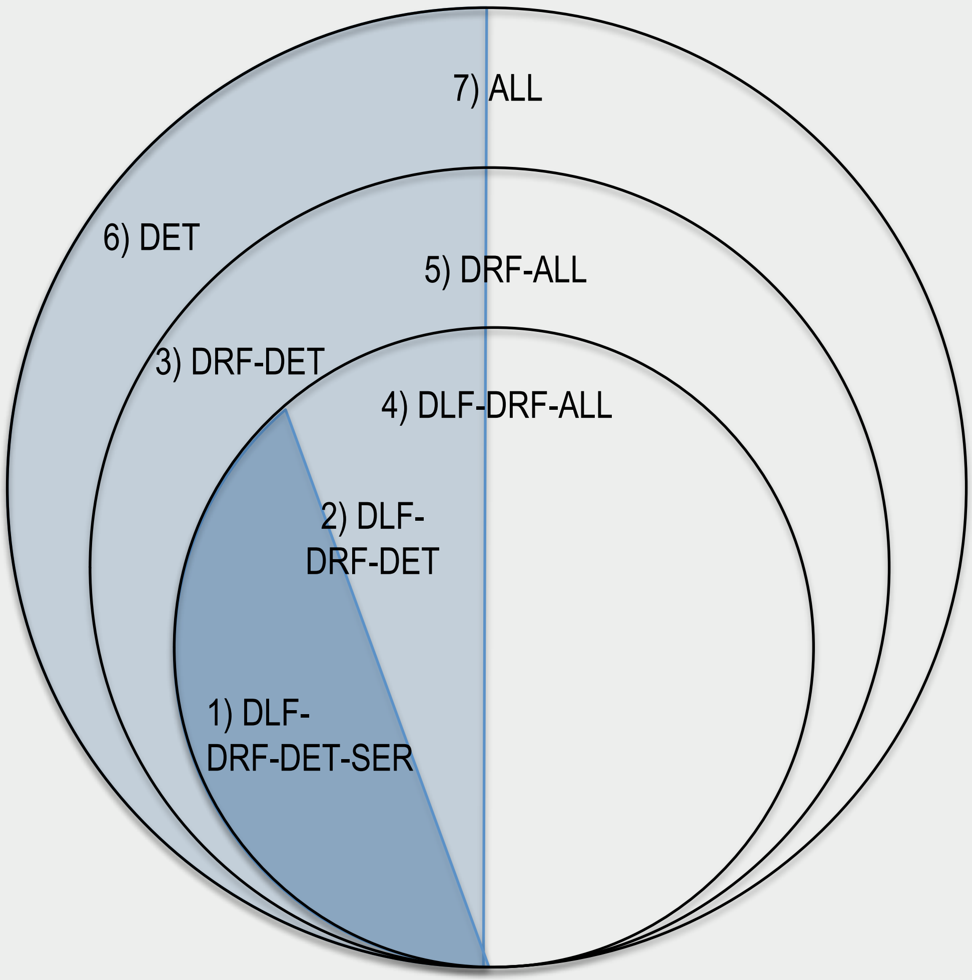
Classification and Properties of Parallel Programs



- Legend
  - DET = Deterministic
  - DRF = Data-Race-Free
  - DLF = DeadLock-Free
  - SER = Serializable
- Subsets of task-parallel constructs can be used to guarantee membership in certain classes e.g.,
- *If an HJ program is data-race-free and only uses async, finish, and phaser constructs (no mutual exclusion), then it is guaranteed to belong to the DLF-DRF-DET class*
- *Adding async await yields programs in the DRF-DET class*
- *Adding isolated yields programs in the DRF-ALL class*

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Summary

- **Habanero-Java is a safe and powerful mid-level parallel language**
- **Safety**
  - Deadlock freedom for any HJ program using finish, async, futures, phasers, isolated
  - Data-race freedom for values accessed through futures and data-driven futures
- **Expressiveness**
  - Orthogonal classes of parallel constructs enables programmers with a basic knowledge of Java to get started quickly with expressing a wide range of parallel patterns
- **Performance**
  - HJ runs on standard JRE's, and has been shown to deliver good performance on a wide range of multicore SMPs (16-core Xeon, 32-core Power7, 64 & 128-thread NIagara2)
- **HJ's mid-level constructs are a good match for**
  - Undergraduate level teaching
  - Multicore software research
  - Future JVM support
  - . . .

Conclusions

- **Habanero-Java is a safe and powerful mid-level parallel language**
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