Avoidance, Detection, and Repair of Bugs in Structured Parallel Programs

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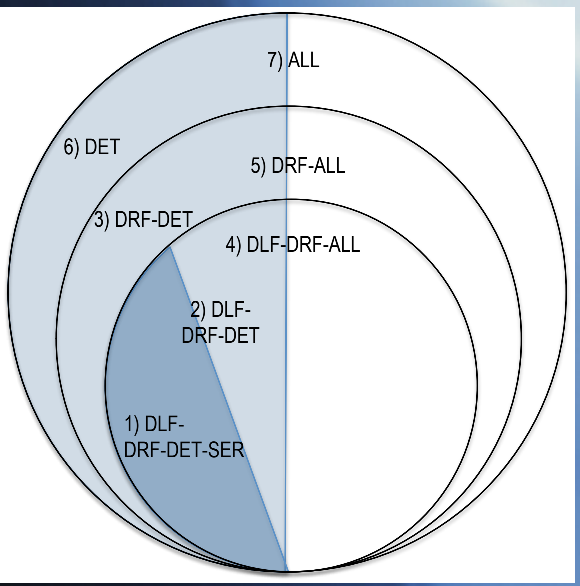
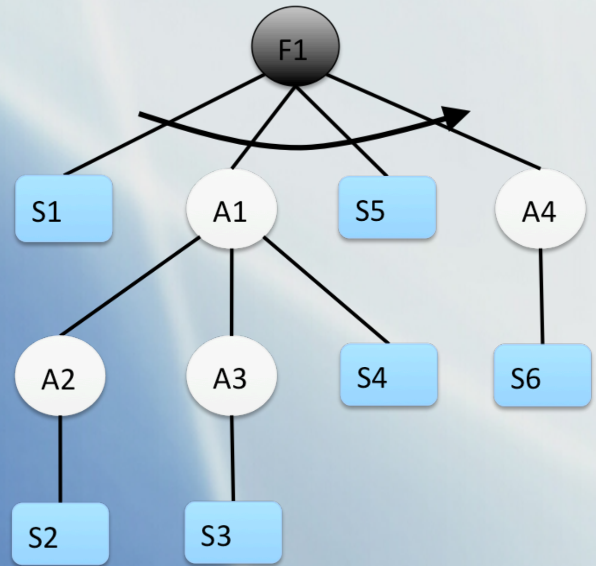
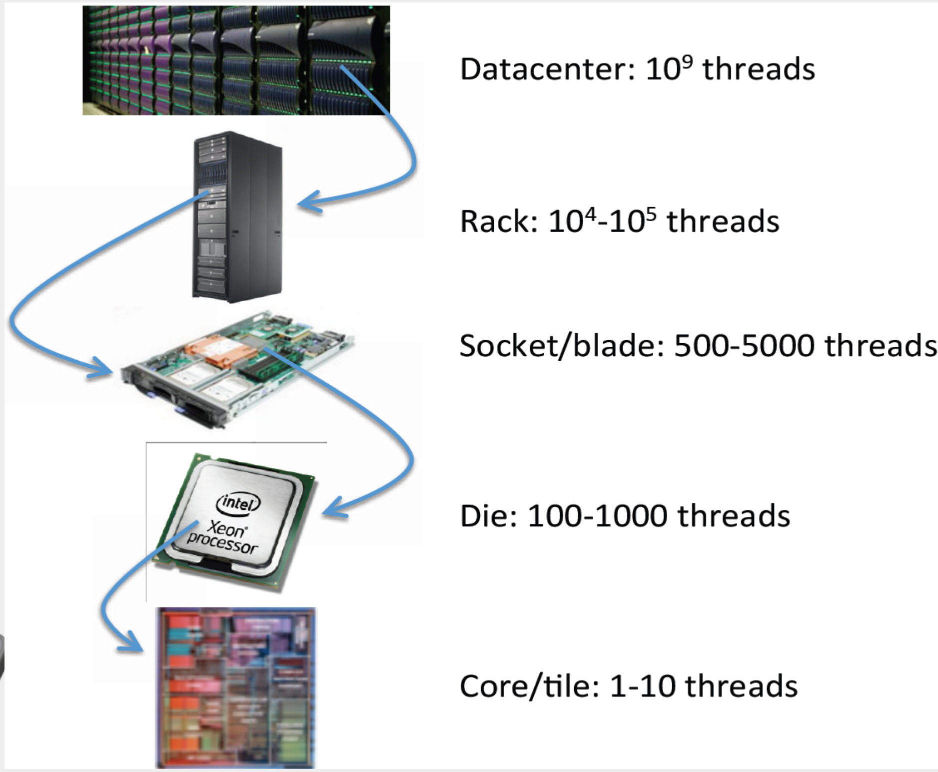




Acknowledgments --- Habanero Extreme Scale Software Group

- **Faculty**
  - Vivek Sarkar
- **Senior Research Scientists**
  - Michael Burke, Kathleen Knobe
- **Research Scientists**
  - Zoran Budimlić, Philippe Charles, Michael Fagan, Akihiro Hayashi, Vivek Kumar, Jun Shirako, Jisheng Zhao
- **Postdoctoral Researcher**
  - Tiago Cogumbreiro
- **Post-MS PhD Students**
  - Kumud Bhandari, Max Grossman, Alina Sbirlea, Rishi Surendran, Sağnak Taşırlar, Nick Vrvilo
- **Pre-MS PhD Students**
  - Prasanth Chatarasi, Arghya Chatterjee,, Ankush Mandal, Yuhan Peng, Jonathan Sharman

With Multicore Processors and Cloud Computing, all Computers are Parallel Computers …



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… and all Software is Parallel by Default!

- New classes of bugs are being encountered in new programming models and frameworks across the full spectrum of parallel systems (embedded, mobile, server, cloud)
- New challenges for software correctness and reliability
  A. **Avoidance** of parallelism/concurrency bugs
  B. **Detection** of parallelism/concurrency bugs
  C. **Repair** of parallelism/concurrency bugs

Context: Rice Habanero Extreme Scale Research Project

Parallel Applications

Structured-parallel execution model

1) Lightweight asynchronous tasks and data transfers

- Creation: *async tasks, future tasks, data-driven tasks*
- Termination: *finish, future get, await*
- Data Transfers: *asyncPut, asyncGet*

2) Locality control for task and data distribution

- Computation and Data Distributions: *hierarchical places, global name space*

3) Inter-task synchronization operations

- Mutual exclusion: *isolated, actors*
- Collective and point-to-point operations: *phasers, accumulators*

Habanero Programming Languages

Habanero Compiler & PIR (Built on LLVM)

Habanero Runtime System (Built on OCR)

Two-level programming model

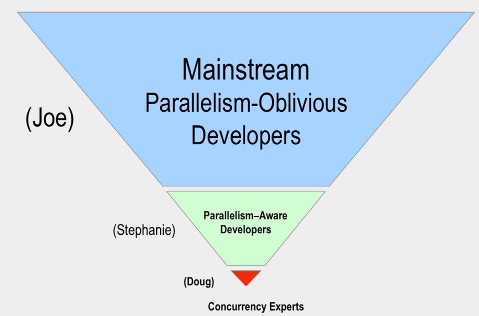
Declarative Coordination Language for Domain Experts:

CnC, DFGL

+

Task-Parallel Languages for Parallelism-aware Developers:

Habanero-C, Habanero-C++, Habanero-Java, Habanero-Scala



Extreme Scale Platforms

Our Approach: Leverage Structured Parallelism

- Programming models should specify what can run in parallel, not how the parallelism should be exploited
  - ➔Specify logical (rather than actual) parallelism with *structured primitives that are accompanied by strong semantic guarantees*
- Compilers should be able to analyze and transform parallel programs
  - ➔Extend foundations of compiler theory so as to *analyze and transform structured parallel programs*
- Runtime systems should be able to efficiently manage larger degrees of parallelism than the underlying hardware
  - ➔Build scalable and adaptive *runtime systems for structured parallelism* that trade off parallelism, locality, energy, and resilience
- Debugging and verification tools should be sound and complete, to the largest extent possible
  - ➔*Use structured parallel abstractions* to help programmers avoid, detect and repair bugs in parallel programs

Structured Primitives in Habanero Execution Model

1) Lightweight asynchronous tasks and data transfers

- Creation: *async tasks, future tasks, data-driven tasks*
- Termination: *finish, future get, await*
- Data Transfers: *asyncPut, asyncGet*

2) Locality control for control and data distribution

- Computation and Data Distributions: *hierarchical places, global name space*

3) Inter-task synchronization operations

- Mutual exclusion: *global/object-based isolation, actors*
- Collective and point-to-point operations: *phasers, accumulators*

Note: these primitives can be used directly as a programming model, or can be targeted by higher level programming models

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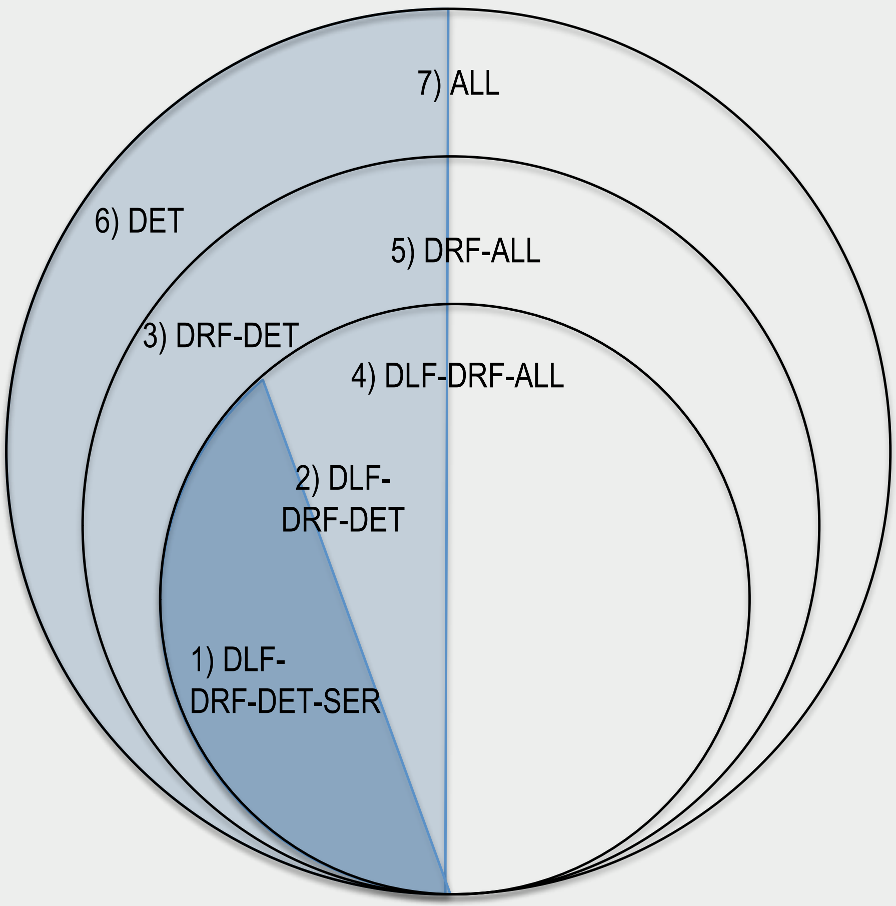
Semantic Classification of Habanero Parallel Programs



- Properties of interest:
  - DLF = DeadLock-Free
  - DRF = Data-Race-Free
  - DET = Structural + Functional Determinism
  - DRF➔DET = DRF implies DET
  - SER = Serial elision
- *If a Habanero program only uses async, finish, and final future constructs, then it is guaranteed to belong to the SER + DLF + (DRF➔DET) class*
- *Adding phasers yields programs in the DLF + (DRF➔DET) class (dropping SER)*
- *Adding async await yields programs in the DRF➔DET class (dropping DRF)*
- *Restricting shared data accesses to futures, isolated, actors yields programs in the DRF-ALL class*
- . . .

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"Habanero-Java: the New Adventures of Old X10." Vincent Cave, Jisheng Zhao, Jun Shirako, Vivek Sarkar PPPJ 2011.

Part A: Overall Approach to Bug Avoidance

- Establish sufficient conditions to ensure that bug cannot appear in any execution of any program that satisfies those conditions

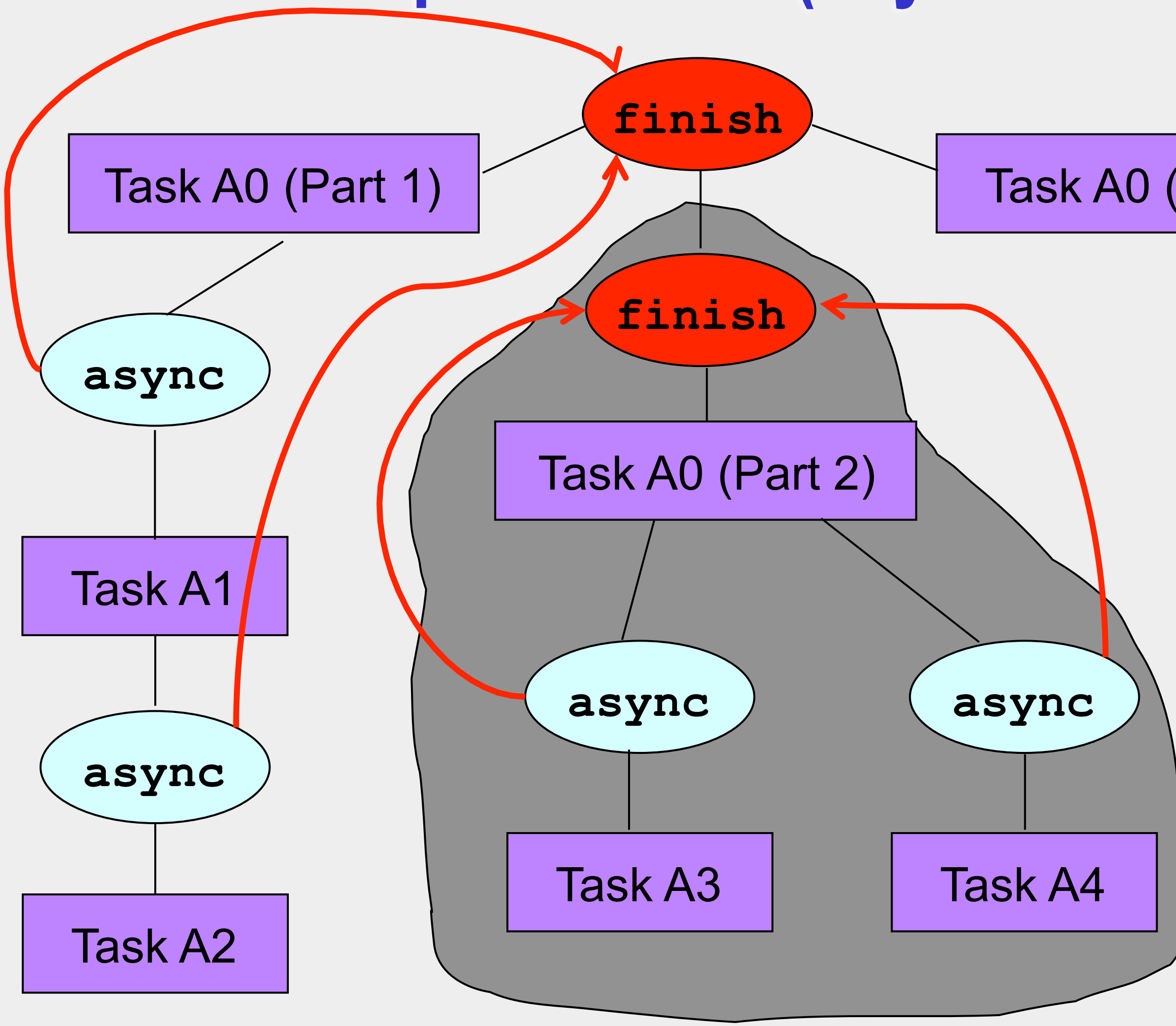
- Example: Deadlock Avoidance

Deadlock Avoidance in Unstructured Fork-Join is hard

It can be hard to avoid deadlocks with unstructured parallelism, e.g.,

```
1. static Thread t1, t2;
2. t1 = new Thread(() -> {t2.join();});
3. t2 = new Thread(() -> {t1.join();});
4. t1.start();
5. t2.start();
```

Deadlock Avoidance can be guaranteed for Structured Fork-Join parallelism (async-finish, spawn-sync, …)




```
finish {
  Task A0 (Part 1);
  async {A1; async A2;}
  try {
    finish {
      Task A0 (Part 2);
      async A3;
      async A4;
    }
  catch (…) { … }
  Task A0 (Part 3);
}
```

Barriers: another example of deadlock (or undefined behavior) with unstructured parallelism

```
// Assume that number of threads is >= 2
#pragma omp parallel
  {
      const int tid = omp_get_thread_num();
      if (tid != 1) {
#pragma omp barrier
      }
  }
```

- Non-conforming program leads to unpredictable results on different platforms
  - Deadlock, silent completion, …
- Similar examples can be created for other models, e.g., MPI

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Phasers: a structured generalization of barriers and point-to-point synchronization

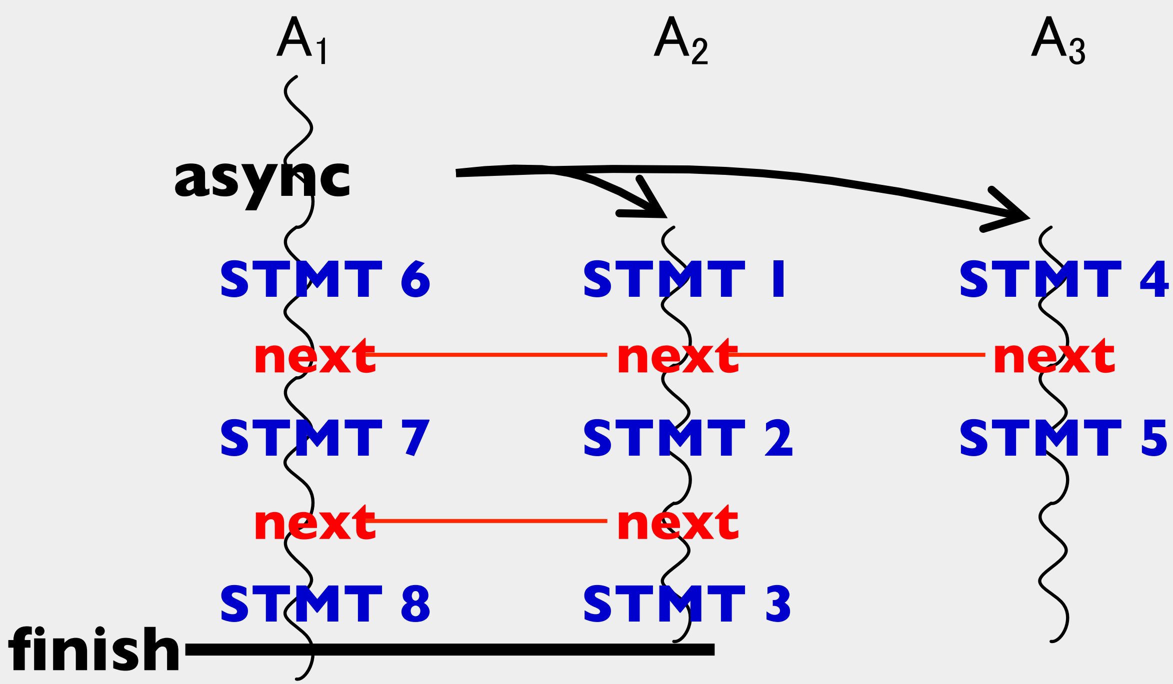
- **Phaser allocation: phaser ph = new phaser(mode);**
  - Phaser **ph** is allocated with registration **mode**
  - Phaser lifetime is limited to scope of Immediately Enclosing Finish (IEF)
  - Registration mode lattice: **SINGLE**

    SINGLE
    |
    SIG_WAIT(default)
    /   \
    SIGNAL   **WAIT**

- **Task creation: async phased (ph$_1$<mode$_1$>, ph$_2$<mode$_2$>, …) <stmt>**
  - Spawned task is registered with **ph$_1$** in **mode$_1$**, **ph$_2$** in **mode$_2$**, …
  - Child task's capabilities must be subset of parent's
  - *Task drops all phaser registrations upon termination*
- **Synchronization: next;**
  - Advance each phaser that activity is registered on to its next phase
  - Semantics depends on registration mode

Deadlock avoidance is guaranteed with phasers …

```
finish {
  phaser ph = new phaser(); //A1
  async phased(ph){ STMT1; next; STMT2; next; STMT3; } //A2
  async phased(ph){ STMT4: next; STMT5; } //A3
                    STMT6; next; STMT7; next; STMT8; //A1
}
```



Tasks A_1 , A_2 , A_3 are registered on phaser ph (can be extended with signal/wait modes)

Dynamic parallelism: # activities registered on phaser can vary

... even with point-to-point synchronization

```
finish for (point[i]: [1:N])
  async phased(ph[i]<SIG>, ph[i-1]<WAIT>,
                     ph[i+1]<WAIT>) {
    while ( true ) {
      A[i] = F(B[i-1], B[i], B[i+1]);
      next; // barrier
      if ( equals(A[i],B[i]) ) break;
      else B[i] = A[i];
    } // while
   } // finish-for-async
```

Exiting from while loop terminates for-async iteration i, and automatically "deregisters" task i from its phasers

Deadlock avoidance proof formalized in Coq

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Futures can deadlock if their references participate in a data race ...

```
future<int> f1=null;
future<int> f2=null;

void main(String[] args) {
  f1 = async<int> {return a1();};
  f2 = async<int> {return a2();};
  . . .
}
```

```
int a1() {
  future<int> tmp=null;
  do {
    tmp=f2;
  } while (tmp == null);
  return tmp.get();
}

int a2() {
  future<int> tmp=null;
  do {
    tmp=f1;
  } while (tmp == null);
  return tmp.get();
}
```

cyclic wait condition

... a sufficient condition to guarantee deadlock avoidance with futures is to ensure that all future references are declared as final variables

Part B: Overall Approach to Bug Detection

- For bugs that are not guaranteed to be avoided, we need to turn to detection
- Focus of our work is on dynamic bug detection for soundness and precision, supported by static analysis for efficiency
- Examples
  1. Data Race Detection
  2. Permission Violation Detection
  3. Commutativity Violation Detection

Data Races

- Two accesses to a shared memory location by two different tasks result in a data race if:
  - At least one of the access is a write, and
  - The program structure *imposes no happens-before ordering* between the two accesses

This definition is sometimes referred to as a *potential* data race

SPD3: Scalable and Precise Dynamic Datarace Detection algorithm

- A parallel sound and precise race detection algorithm for async and finish constructs
- Two components:
  - Dynamic Program Structure Tree (DPST)
    - To identify potentially parallel accesses
  - Access Summary
    - To identify interfering accesses
- "Scalable and Precise Dynamic Data Race Detection for Structured Parallelism". Raghavan Raman, Jisheng Zhao, Vivek Sarkar, Martin Vechev, Eran Yahav. [PLDI '12]

Dynamic Program Structure Tree (DPST)

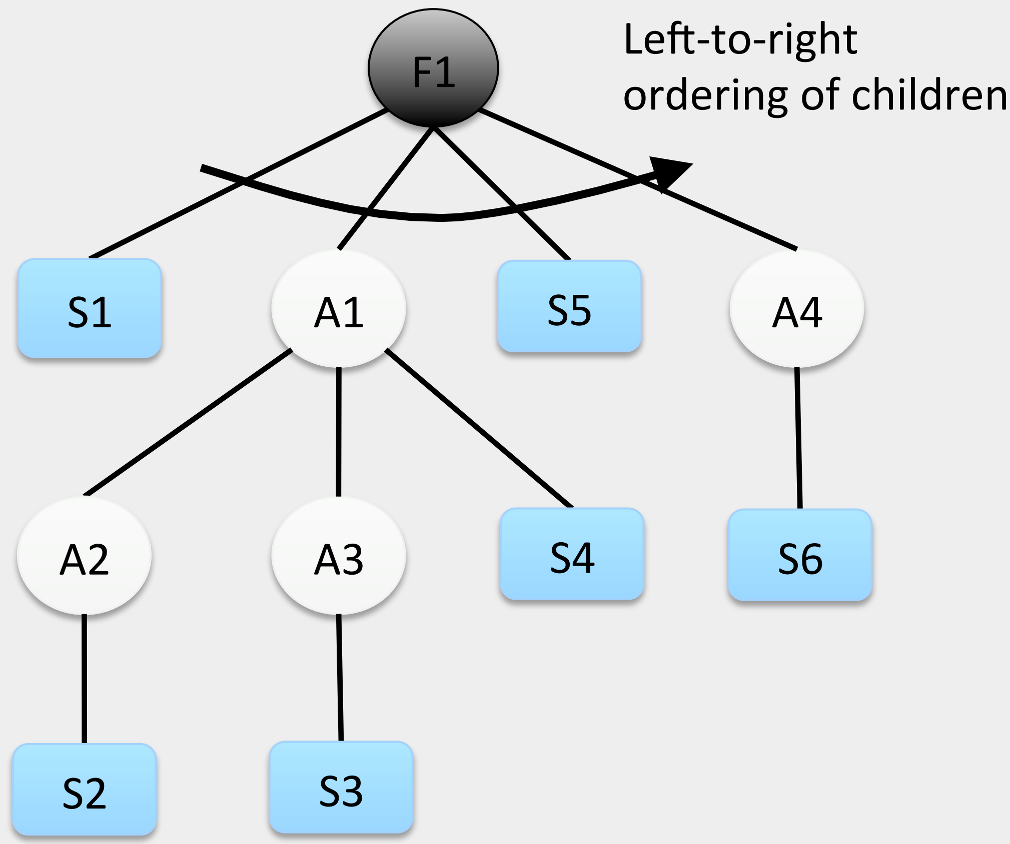
- Tree that maintains parent-child relationships among async, finish, and step instances
  - Internal nodes represent async and finish instances
  - Leaf nodes represent step instances

- Step
  - Maximal sequence of statements with no async or finish

- Children of a node are ordered from left-to-right
  - Reflects the sequencing of computations that belong to the same task

DPST Example

```
finish { // F1
    S1;
    async { // A1
        async { // A2
            S2;
        }
        async { // A3
            S3;
        }
        S4;
    }
    S5;
    async { // A4
        S6;
    }
}
```



DPST Properties resulting from Structured Parallelism

- Every execution of a program with the same input produces the same DPST
  - If no data race is detected

- Path from a leaf to the root stays invariant as the tree grows

- All computations happen in leaves
  - May-happen-in-parallel checks will be done only between leaves

Identifying Parallel Accesses using DPST

DMHP (S, S')

1) L := LCA (S, S')
2) C := child of L that is
   ancestor of S
3) If C is async
   return true
   Else return false

Assuming S is to the left of S' in the DPST

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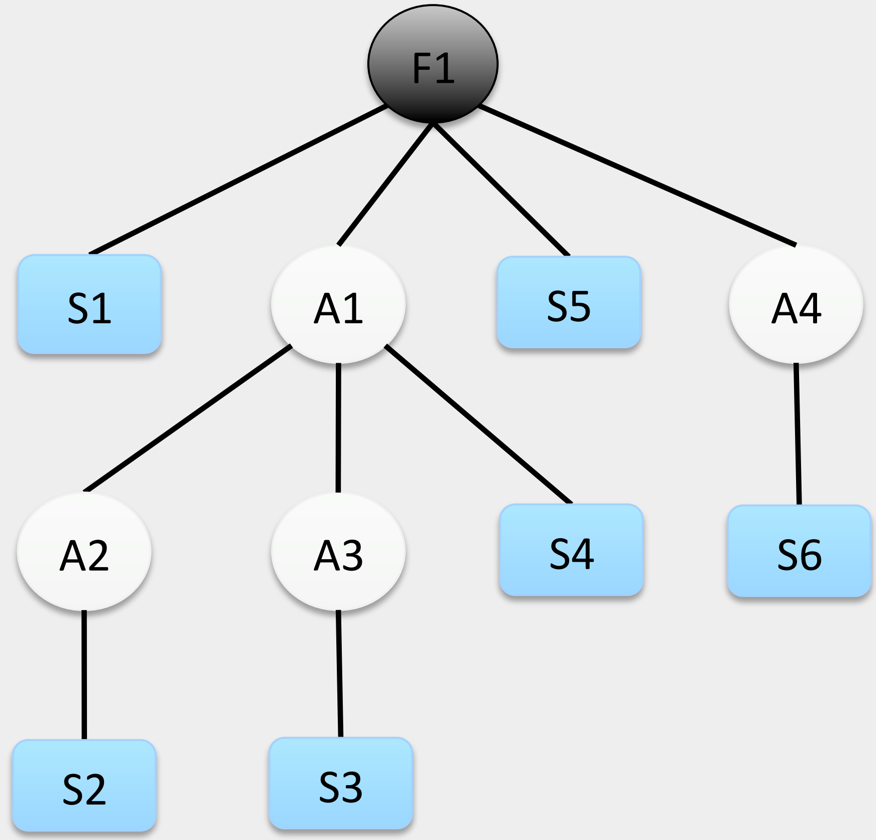

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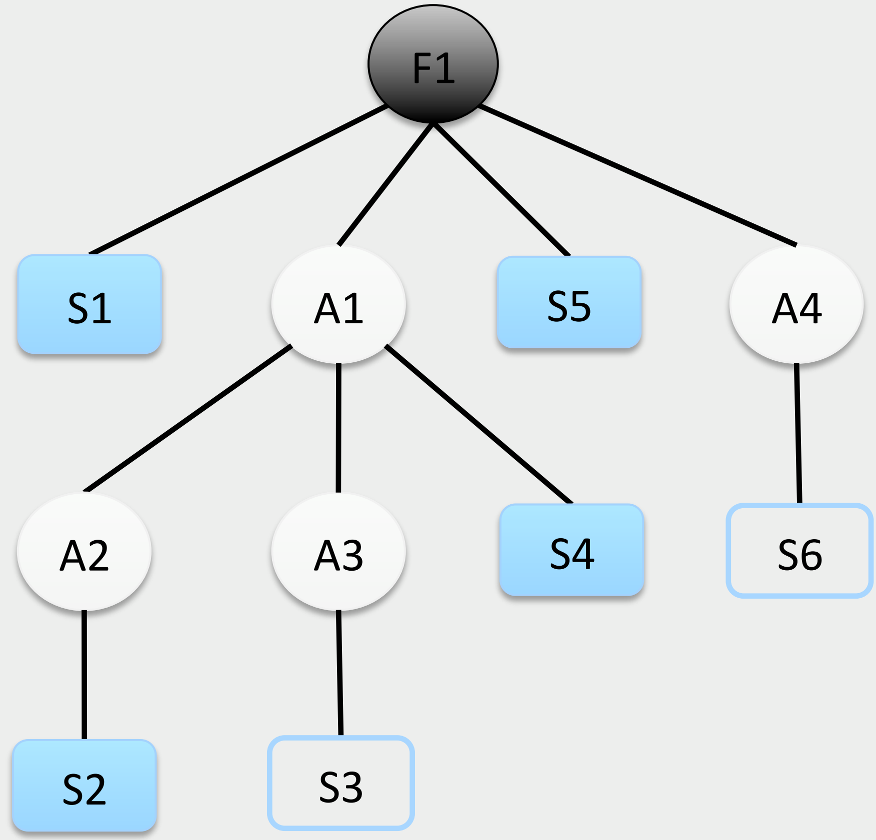

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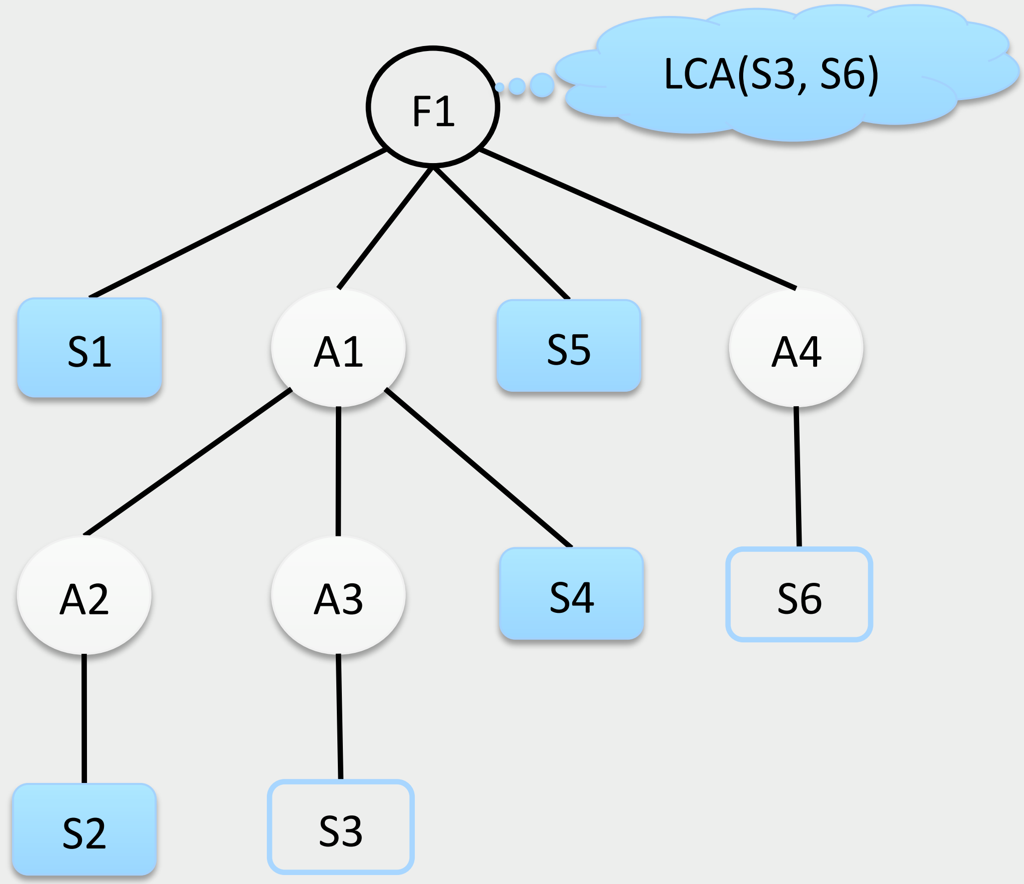

Identifying Parallel Accesses using DPST

DMHP (S, S’)

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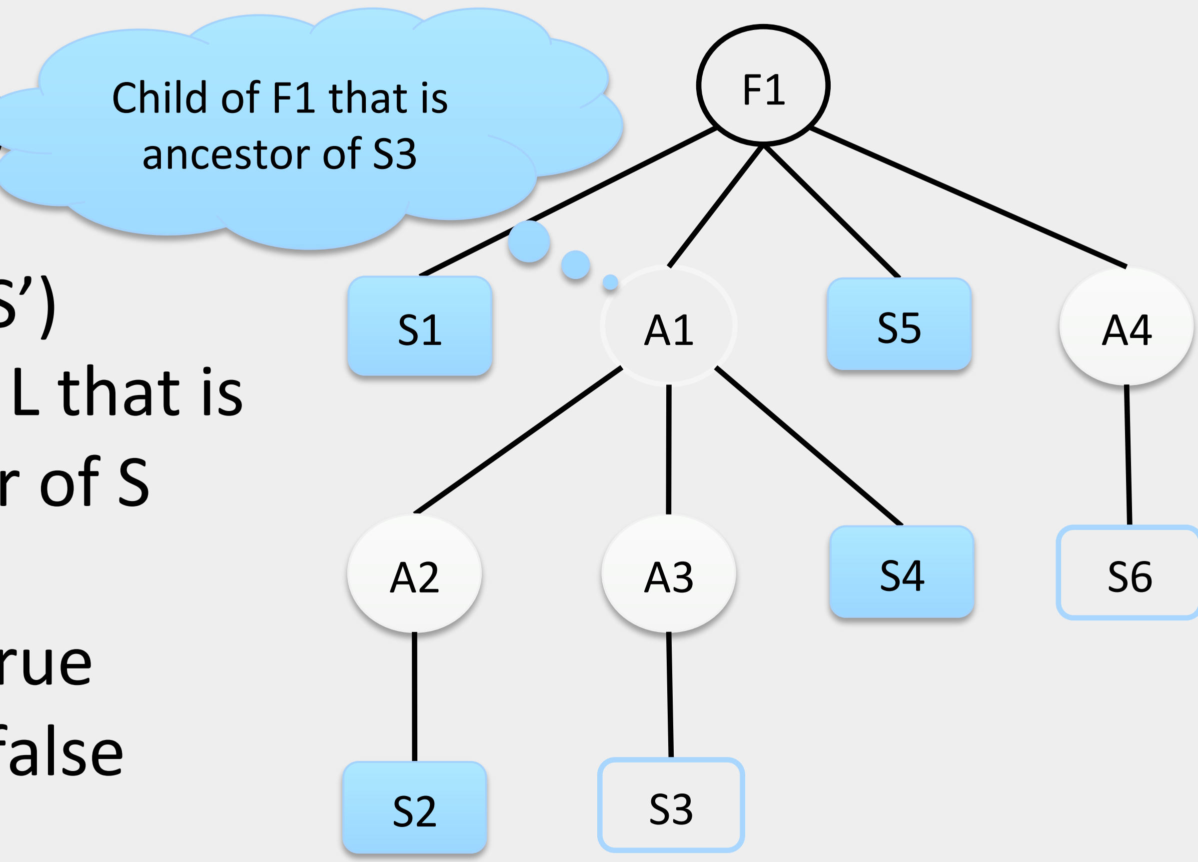

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Identifying Parallel Accesses using DPST

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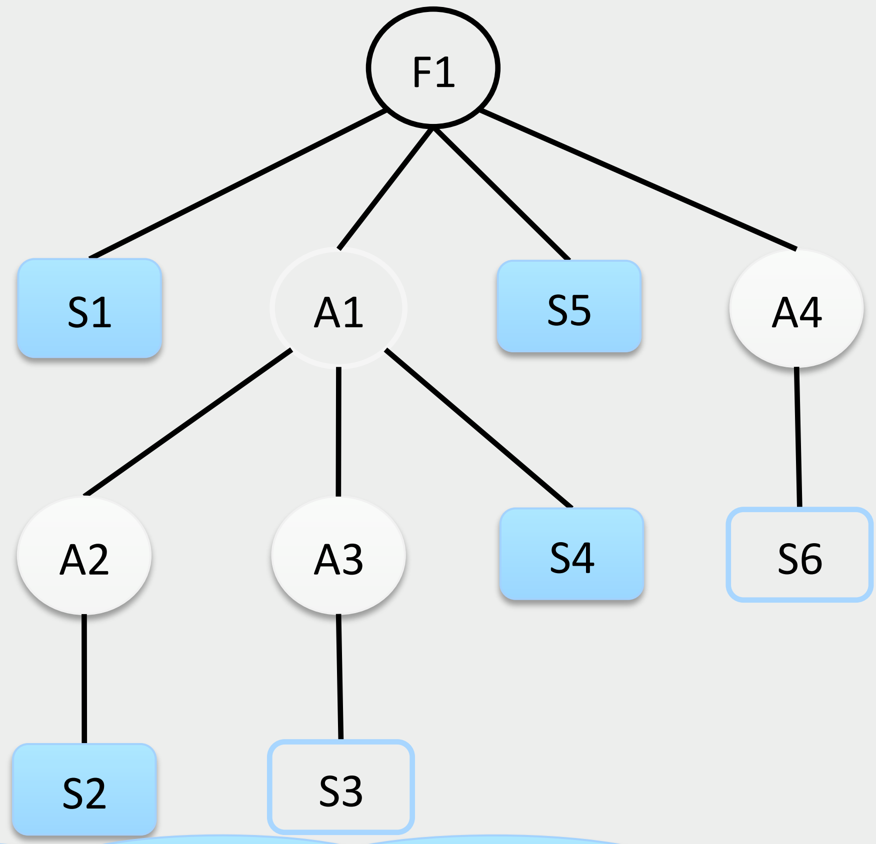

A1 is an async => DMHP(S3, S6) = true

Identifying Parallel Accesses using DPST

DMHP (S, S')

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3) If C is async
   return true
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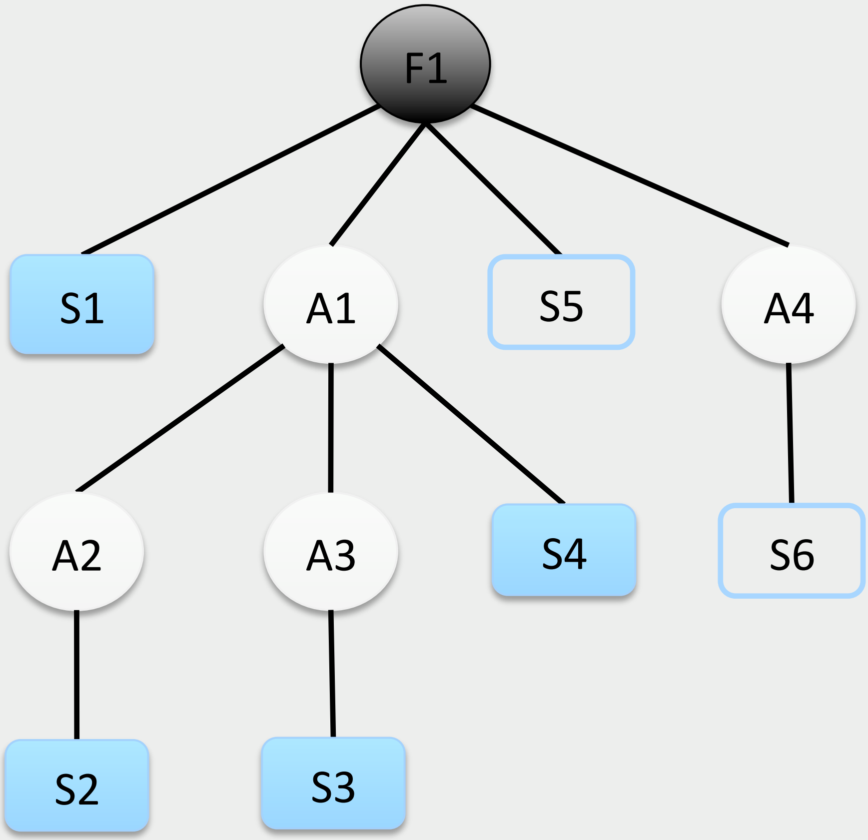

Identifying Parallel Accesses using DPST

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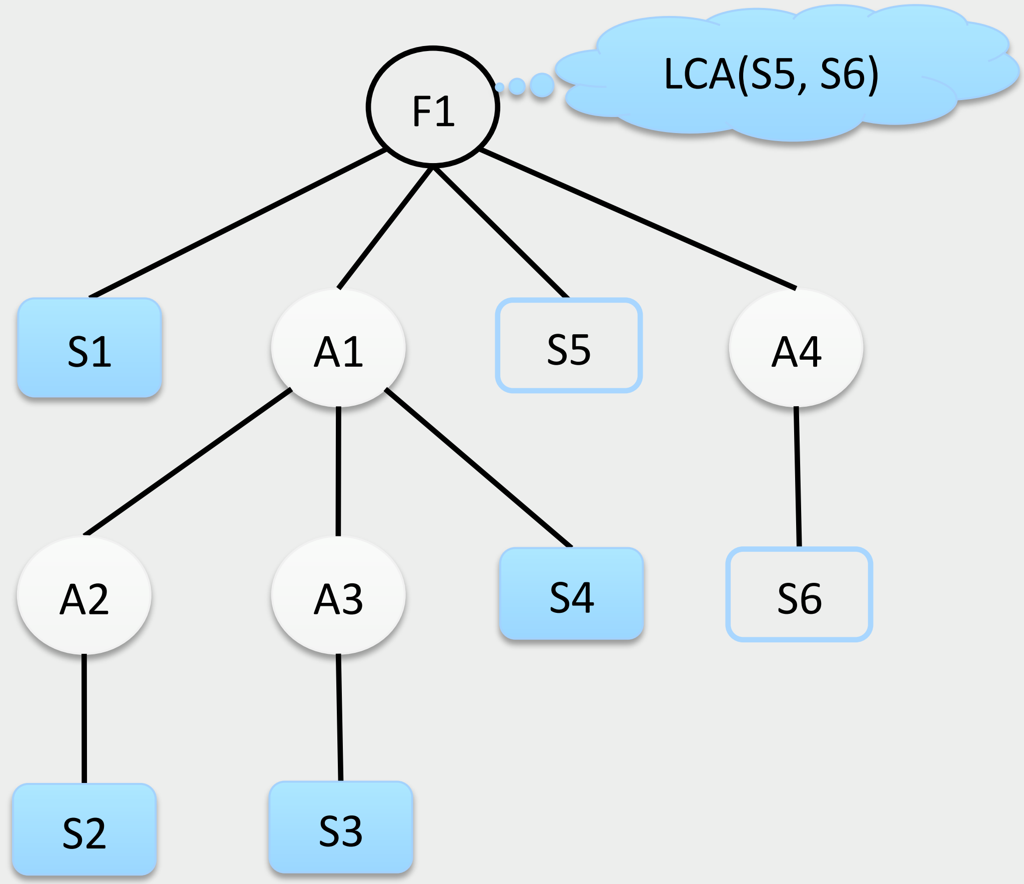

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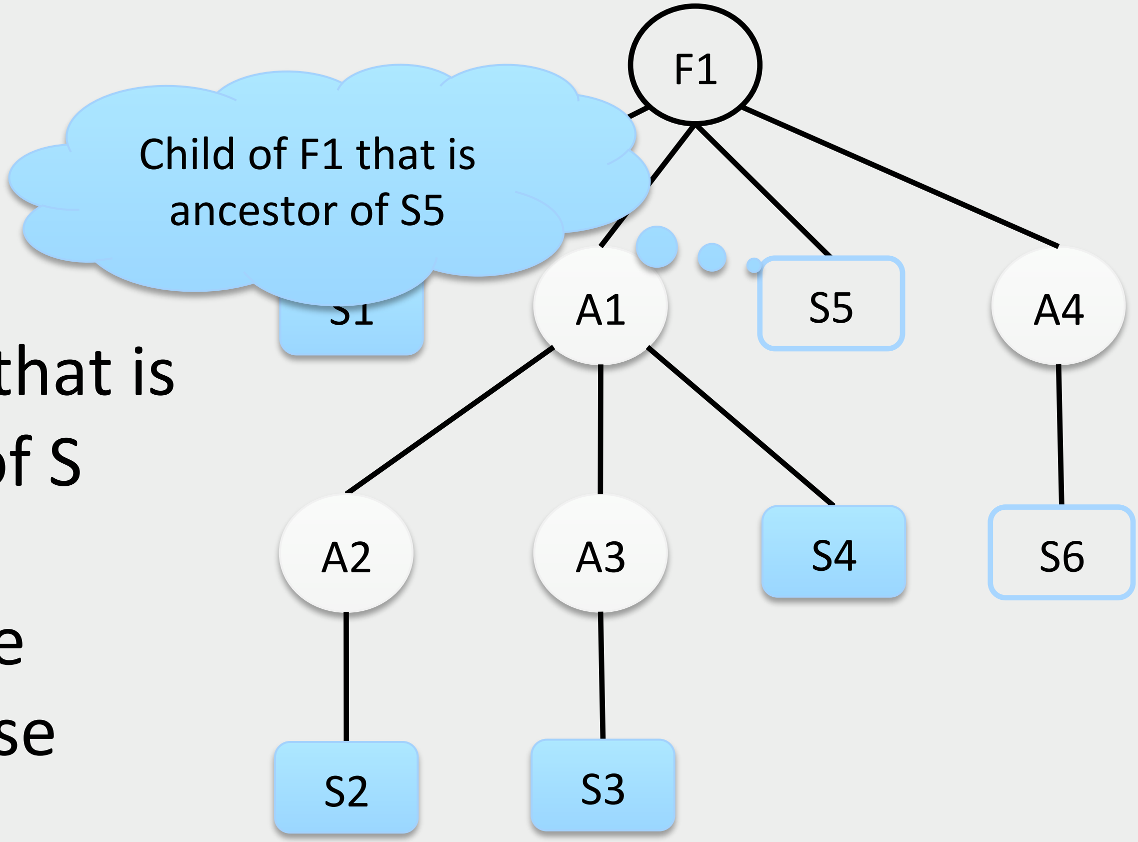

Identifying Parallel Accesses using DPST

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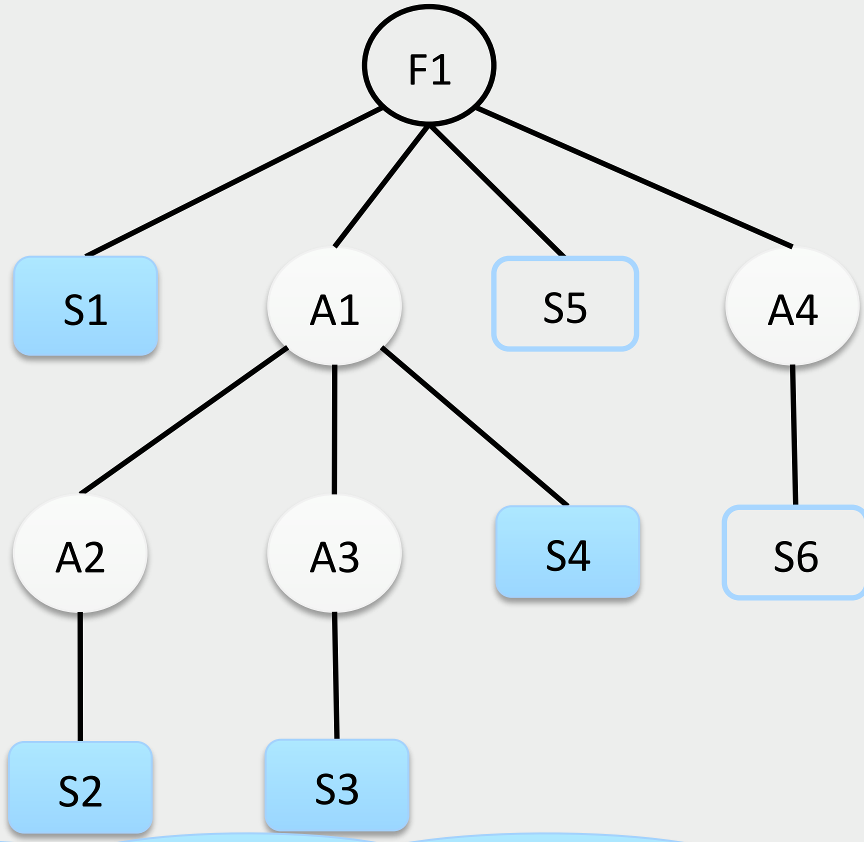

S5 is NOT an async => DMHP(S5, S6) = false

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Related Work: A Comparison

Properties	OTFDAA [PLDI '89]	Offset-Span [SC '91]	SP-bags [SPAA '97]	SP-hybrid [SPAA '04]	FastTrack [PLDI '09]	ESP-bags [RV '10]	SPD3 [PLDI '12]
Target Language	Nested Fork-Join & Synchronization operations	Nested Fork-Join	Spawn-Sync	Spawn-Sync	Unstructured Fork-Join	Async-Finish	Async-Finish
Space Overhead per memory location	O(m)	O(1)	O(1)	O(1)	O(N)	O(1)	O(1)
Guarantees	Per-Schedule	Per-Input	Per-Input	Per-Input	Per-Input	Per-Input	Per-Input
Empirical Evaluation	No	Minimal	Yes	No	Yes	Yes	Yes
Execute Program in Parallel	Yes	Yes	No	Yes	Yes	No	Yes
Dependent on Scheduling technique	No	No	Yes	Yes	No	Yes	No

OTFDAA – On the fly detection of access anomalies
m – number of threads executing the program
N – maximum logical concurrency in the program

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Another Example: Detection of Permission Violations

- Permissions check for “high-level” data races
- Advances in Permission Types:
  - Aliased write permissions
  - Dynamic permission acquires/releases
  - Storable permissions
- Extensions:
  - Array-Based Parallelism
  - Object-based isolation
- “Practical Permissions for Race-Free Parallelism”. Edwin Westbrook, Jisheng Zhao, Zoran Budimlic, Vivek Sarkar, ECOOP ’12.

Permission Types in Code

```
write void insert (write Node n) {
  n.next = next;
  next = n;
}

read bool search (int i) {
  if (data == i)
    return true;
  else if (next == null)
    return false;
  else return next.search (i);
}
```

Gradual Typing: System inserts acquires as needed

```
void insert (Node n) {

  n.next = next; next = n;

}

bool search (int i) {

  if (data == i) return true;
  else if (next == null) return false;
  else return next.search (i);

}
```

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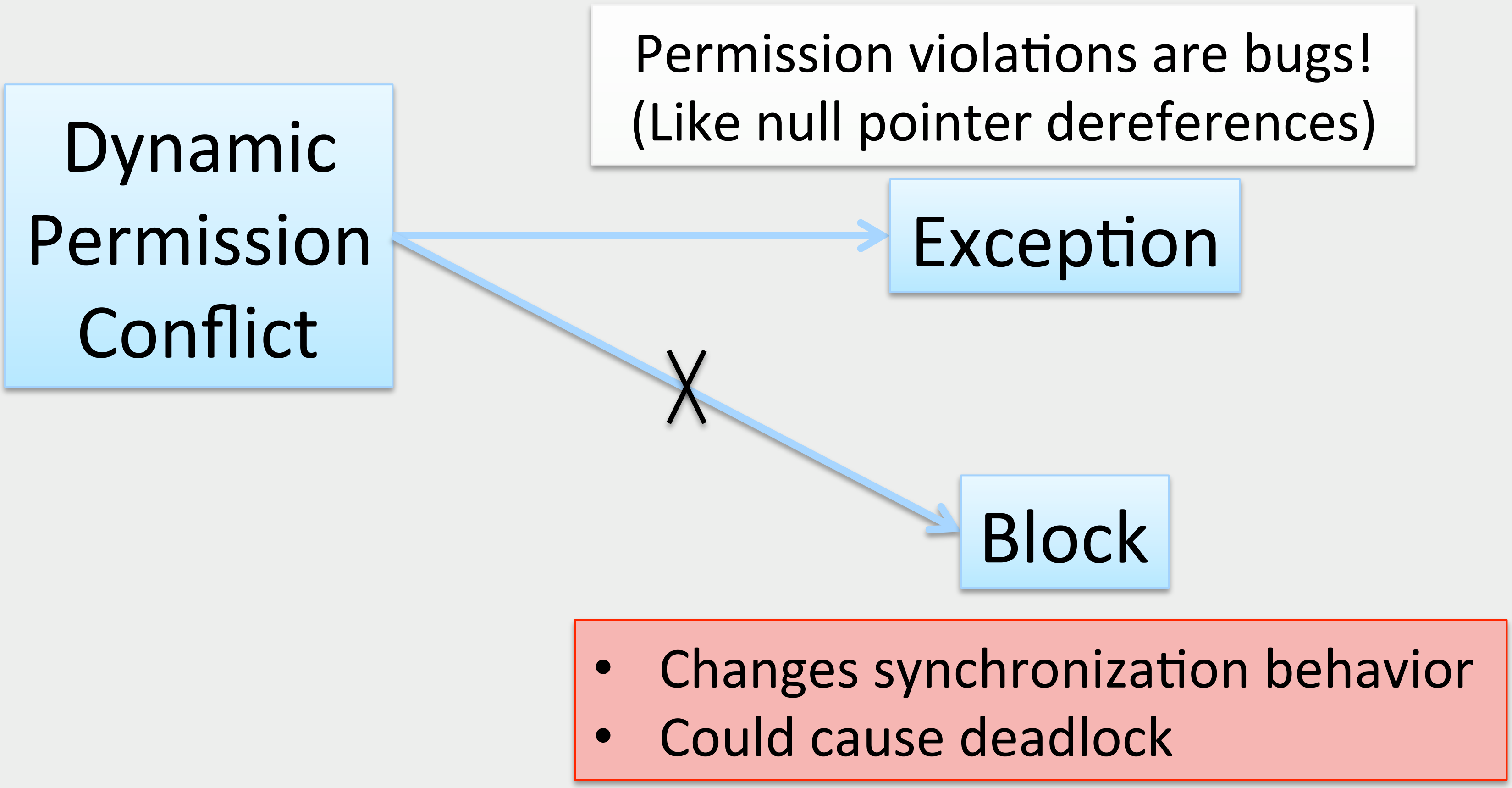
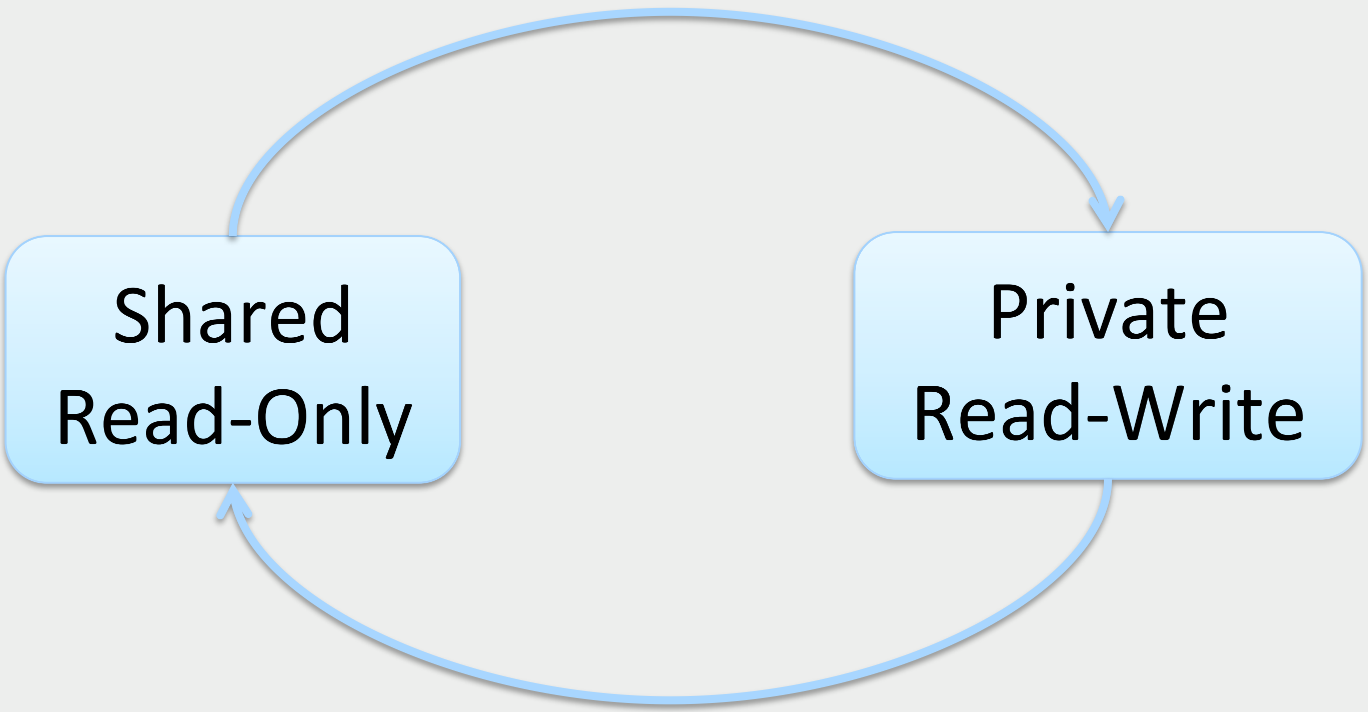
Acquires & Fail-Stop Semantics



Object Modes



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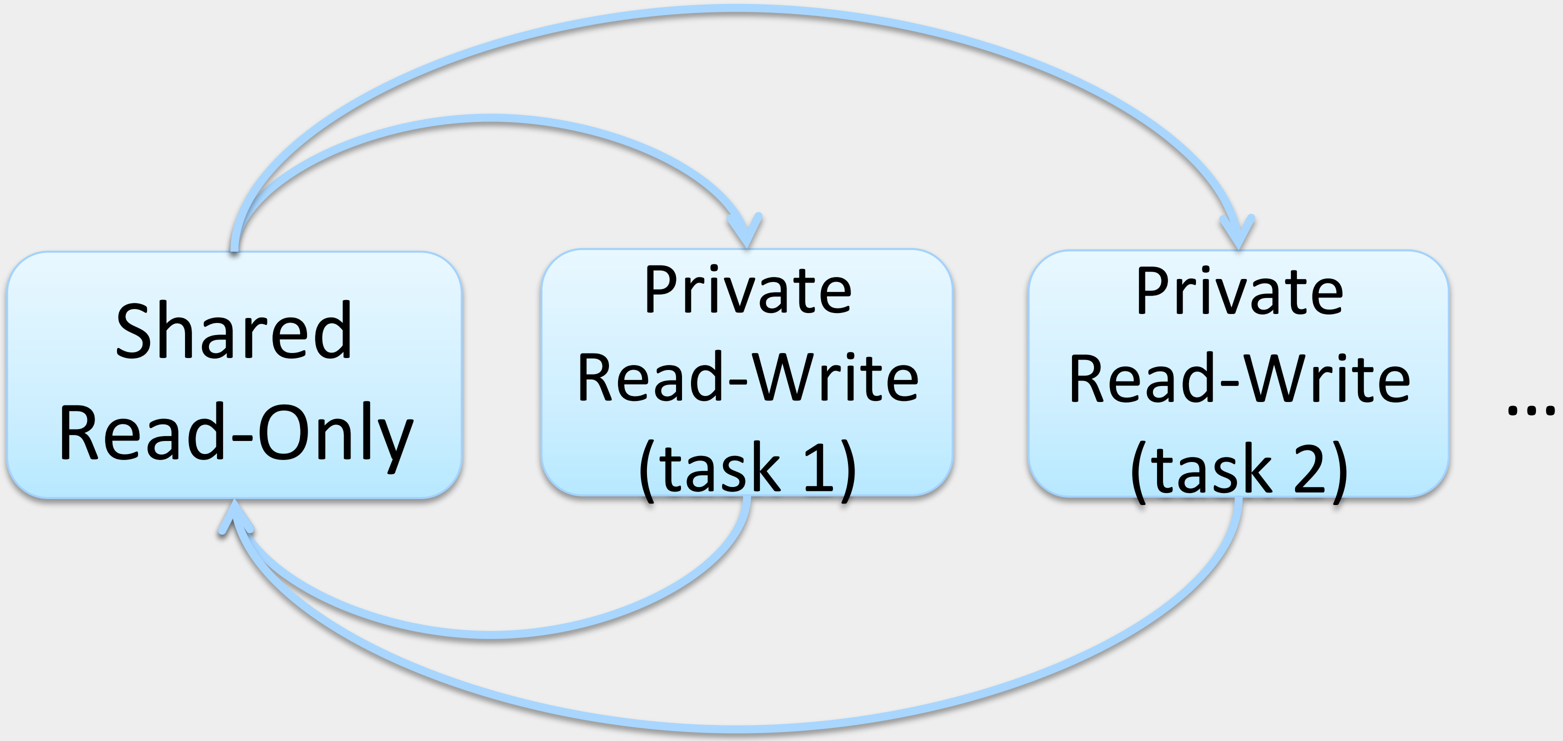
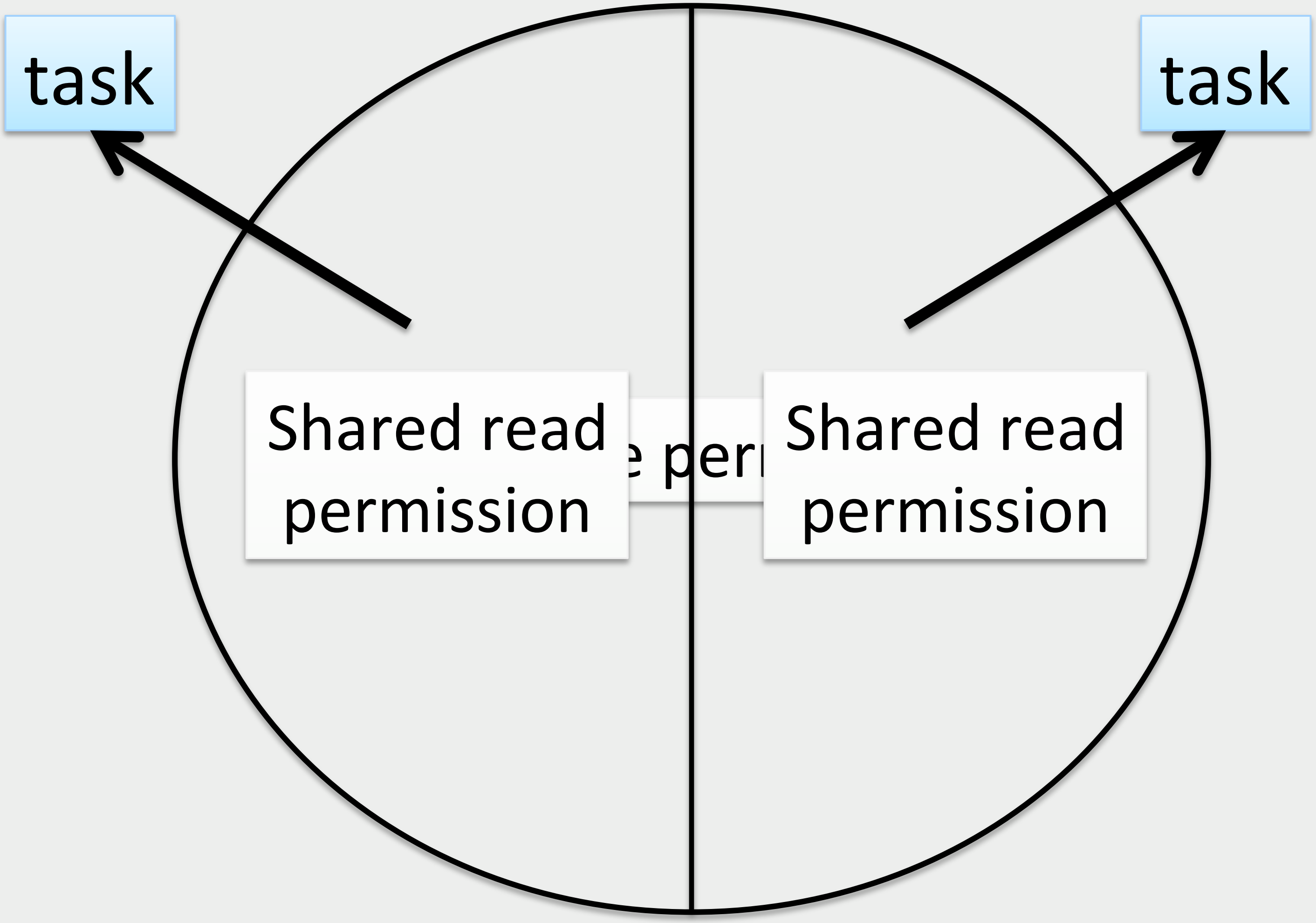
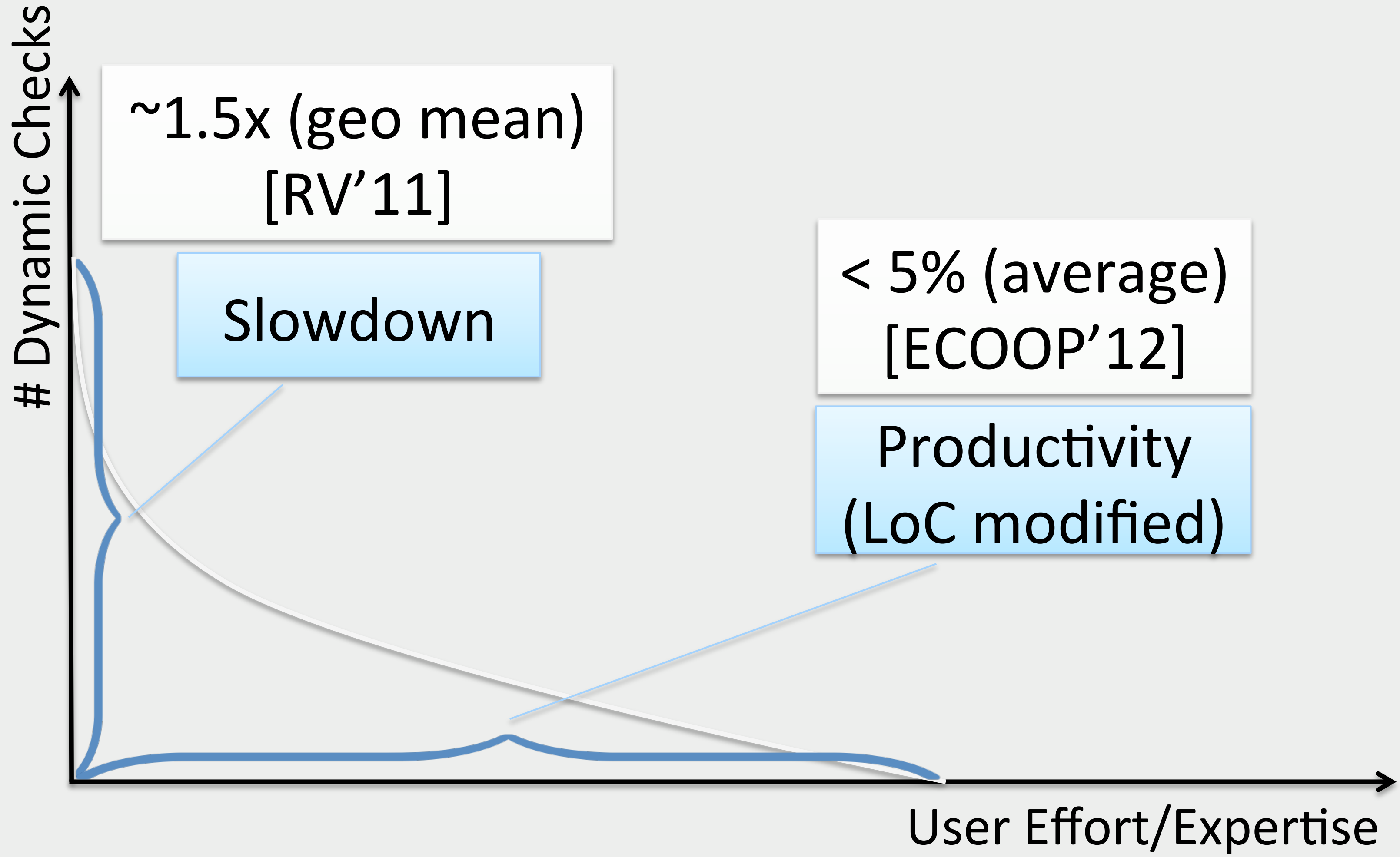


Fractional Permissions



Gradual Typing enables Trade-off between User Effort and Dynamic Checks



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Dynamic Determinism Checking for Structured Parallelism [WoDet'14]

- HJd = Habanero Java with determinism
  - Builds on our prior race-freedom work [RV'11,ECOOP'12]
- Determinism is checked dynamically
  - For application code, not parallel libraries
- Determinism failures throw exceptions
  - Because non-determinism is a bug!
- Checking itself uses a deterministic structure
- Leads to low overhead: 1.26x slowdown!

Two Sorts of Code

1. High-performance parallel libraries
   - Uses complex and subtle parallel constructs
   - Written by concurrency experts: the 1%
2. Deterministic application code
   - Uses parallel libraries in a deterministic way
   - Parallelism behavior is straightforward
   - Written by everybody else: the 99%

We focus on application code

Approach: Determinism via Commutativity

1. Identify pairs of library operations which commute
   - Operations = parallel library primitives (the 1%)
   - Verified independently of this work
2. Dynamic checking of the application code (the 99%)
   - Detect commutativity violations using the DPST
   - Ensures no non-commuting methods could possibly run in parallel

Example: Counting Factors in Parallel

```
class CountFactors {
  int countFactors (int n) {
    AtomicInteger cnt
      = new AtomicInteger();
    finish {
      for (int i = 2; i < n; ++i)
        async {
          if (n % i == 0)
            cnt.increment();
        }}
    return cnt.get ();
}}
```

Fork task

Join child tasks

Increment cnt in parallel

Get result after finish

Specifying Commutativity for Libraries

- Methods annotated with “commutativity sets”
  - Each pair of methods in set commute
- Syntax:

```
@CommSets{S1, …,Sn} <method sig>
```

  - States method is in sets S_1 through S_n
  - Commutes with all other methods in these sets

Commutativity Sets for AtomicInteger

```
final class AtomicInteger {
  @CommSets{"read"} int get () { ... }
  @CommSets{"modify"} void increment()
                              { ... }
  @CommSets{"modify"} void decrement()
                              { ... }
  @CommSets{"read","modify"} int initValue()
                              { ... }
  int incrementAndGet () { ... }
```

get commutes with itself

inc/dec commute with themselves and each other

Commutes with anything

Commutes with nothing (not even itself)

Part C: Test-Driven Repair of Data Races

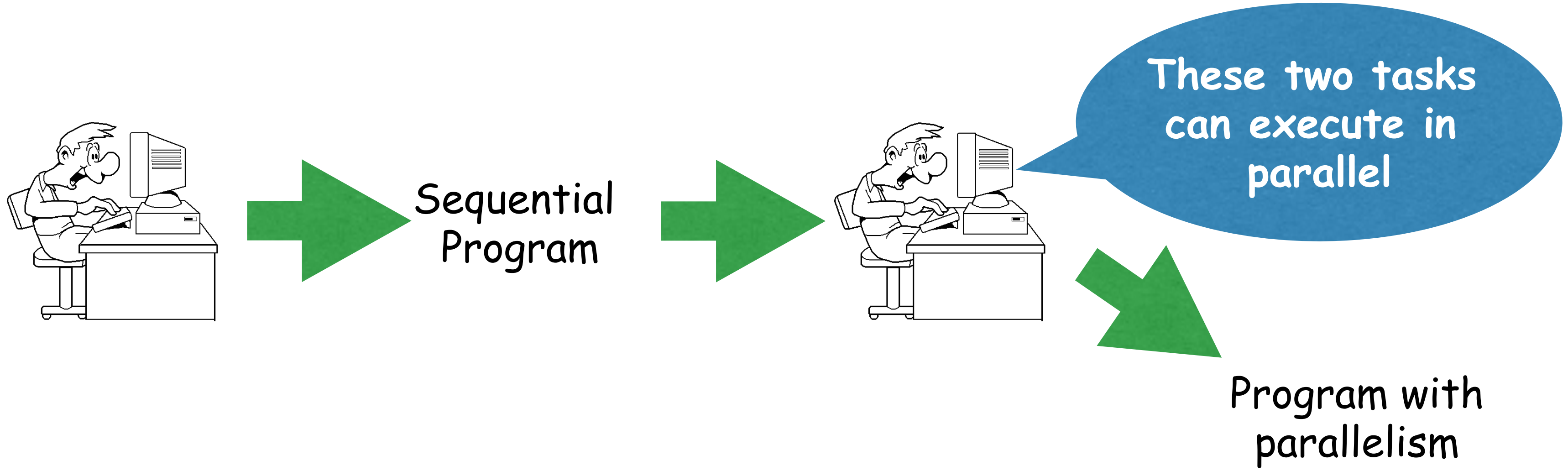
- **Use test inputs to drive program repair by inserting finish statements to ensure that no races remain for the test inputs**
- **Goal: maximize available parallelism after repair**
- **The newly inserted finish statements must respect the lexical scope of the draft program**
- **The complete program after insertion of finish statements must have the same semantics as its linearized version (eliding parallel constructs)**
- **"Test-Driven Repair of Data Races in Structured Parallel Programs". Rishi Surendran, Raghavan Raman, Swarat Chaudhuri, John Mellor-Crummey, and Vivek Sarkar. PLDI 2014.**

Parallel Software Development: Current Practice

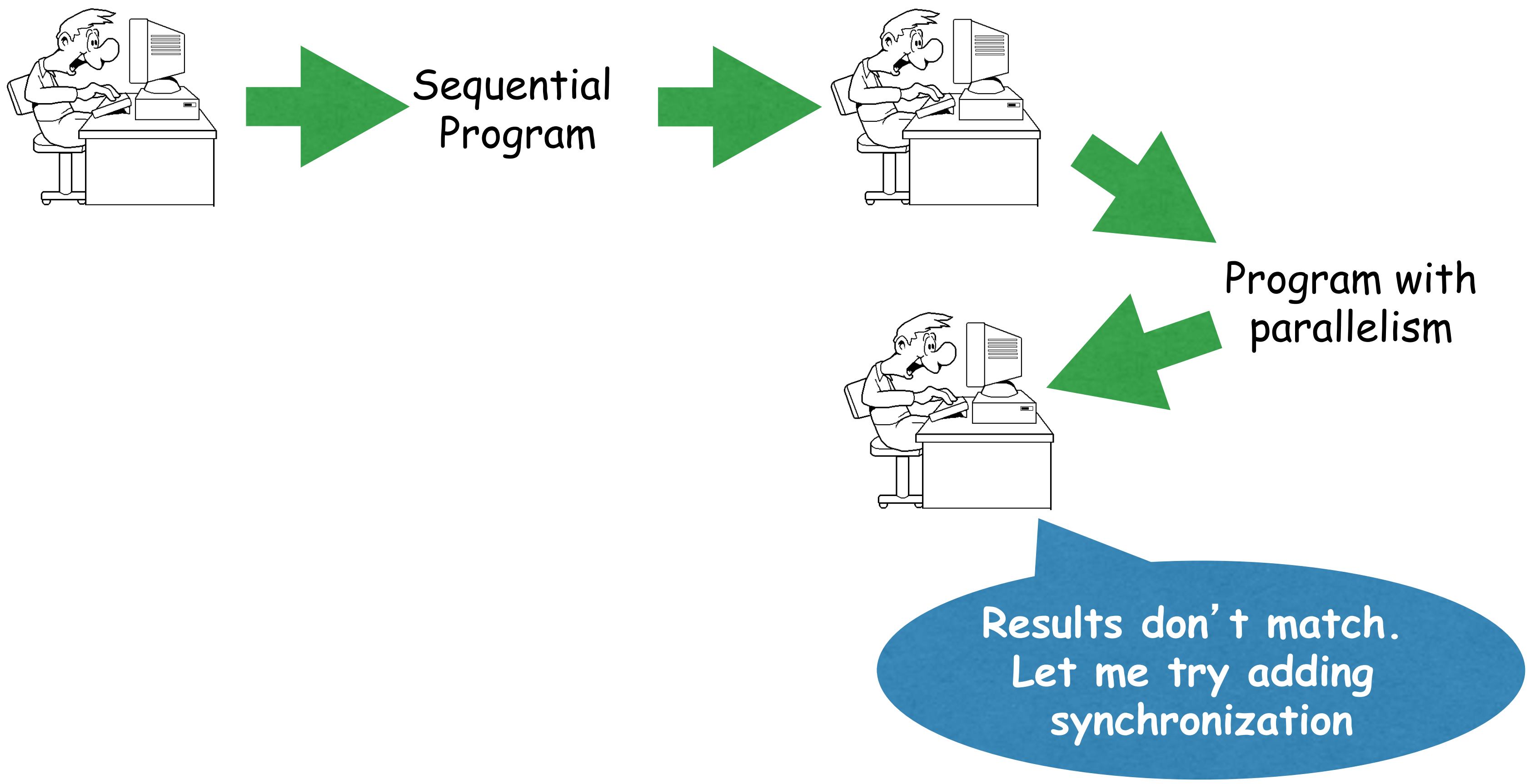
Sequential Program

That was easy

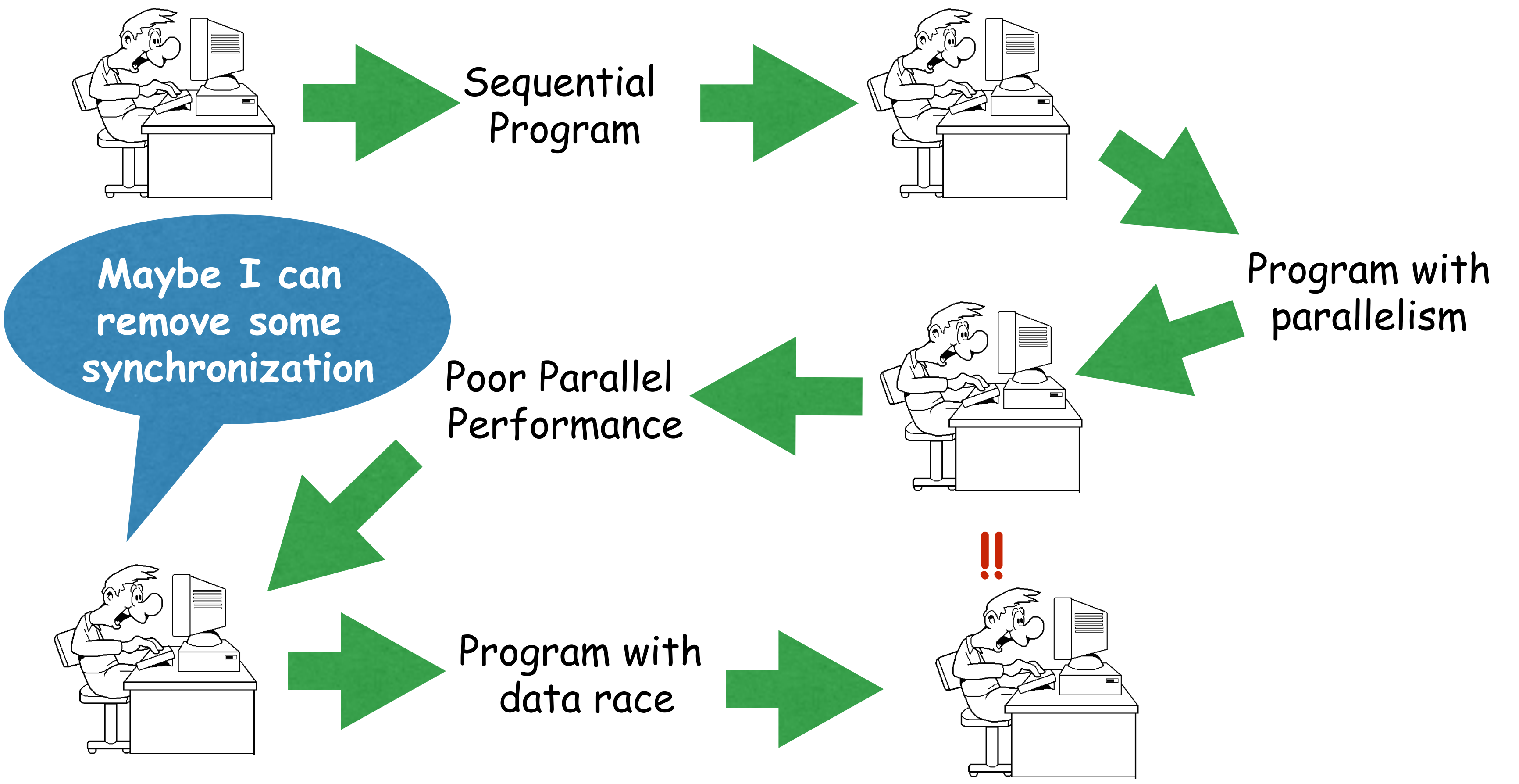
Parallel Software Development: Current Practice



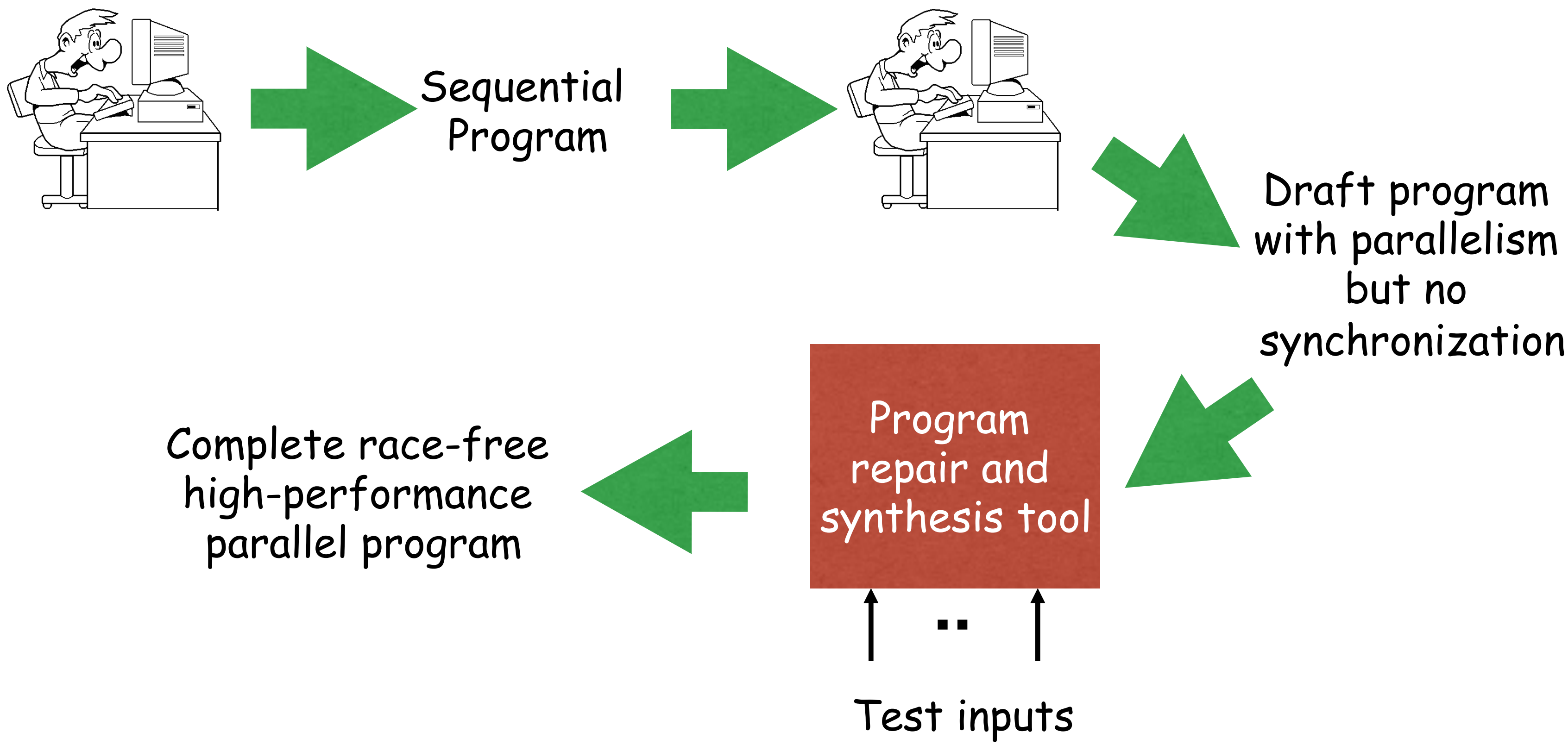
Parallel Software Development: Current Practice



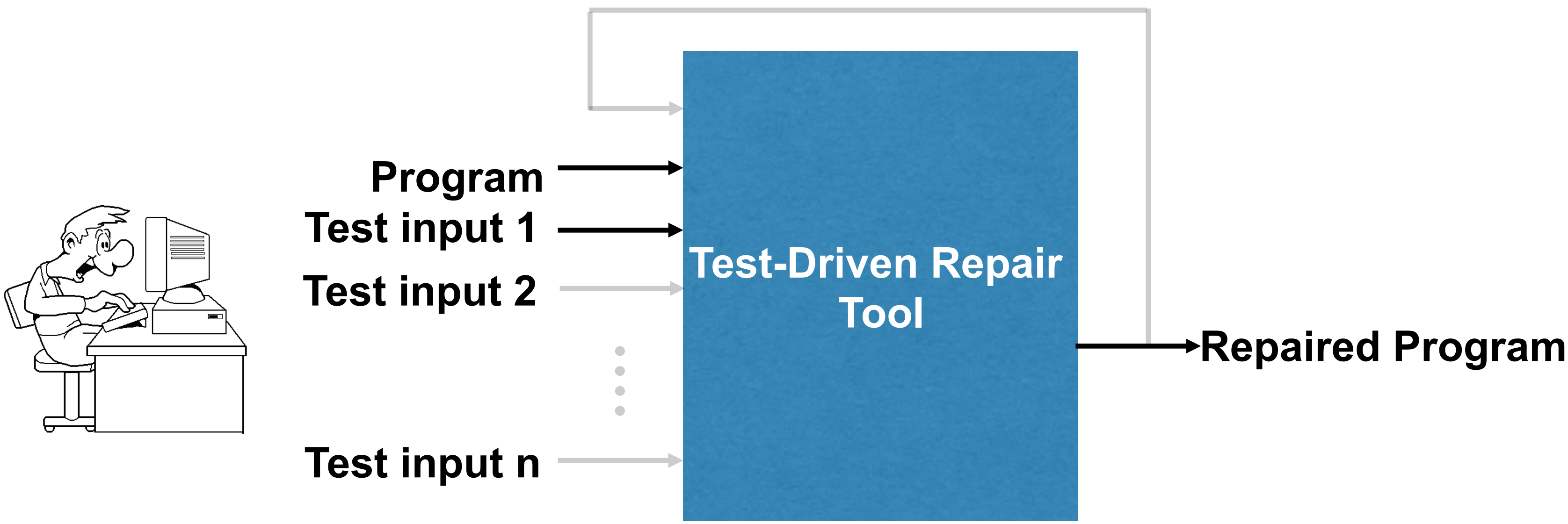
Parallel Software Development: Current Practice



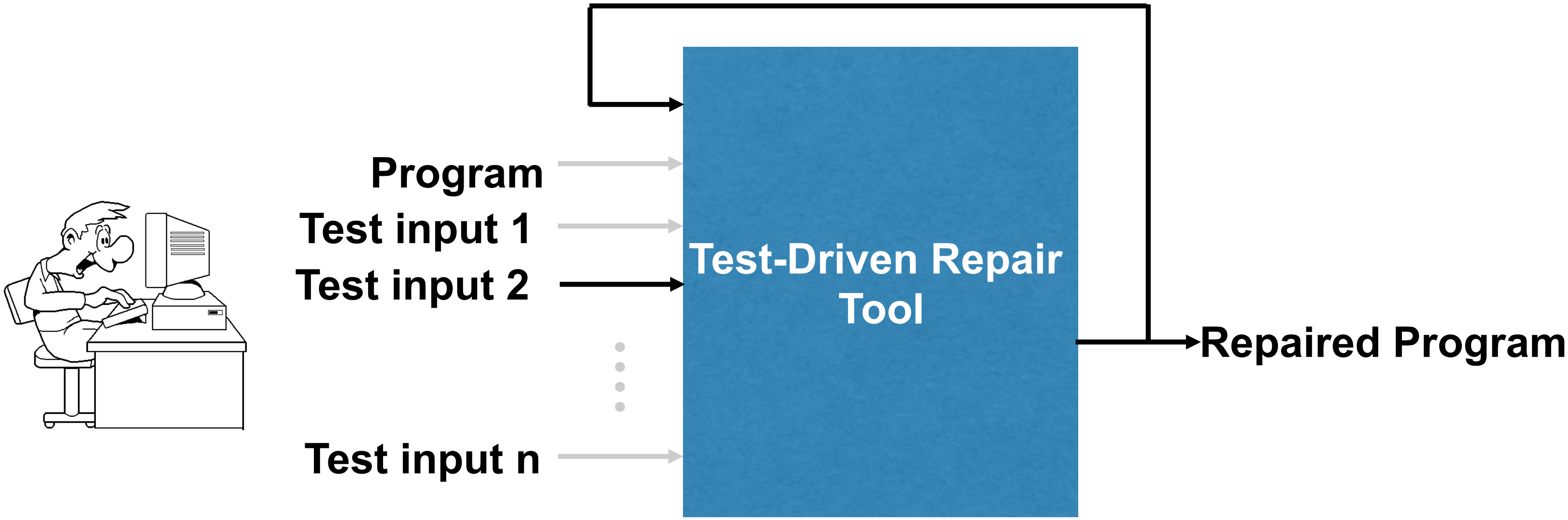
Parallel Software Development: Our Vision



High Level View of Test-Driven Program Repair

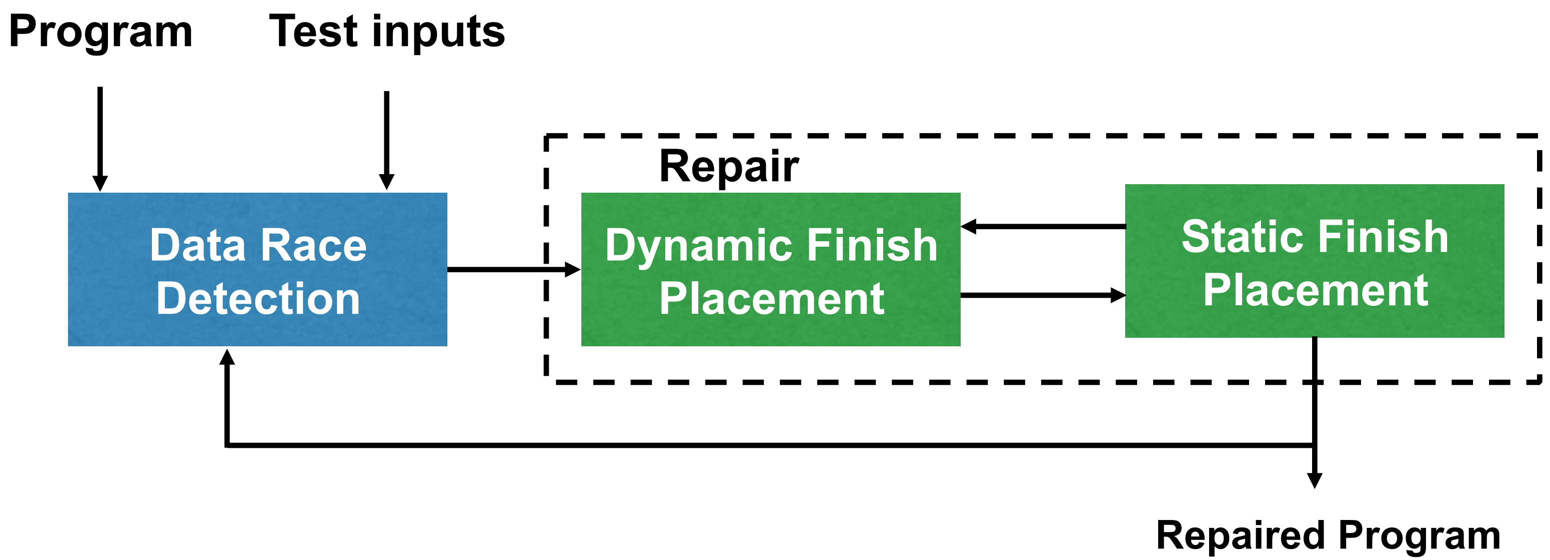


High Level View of Test-Driven Program Repair



Tool guarantees data race freedom in repaired program for all test inputs

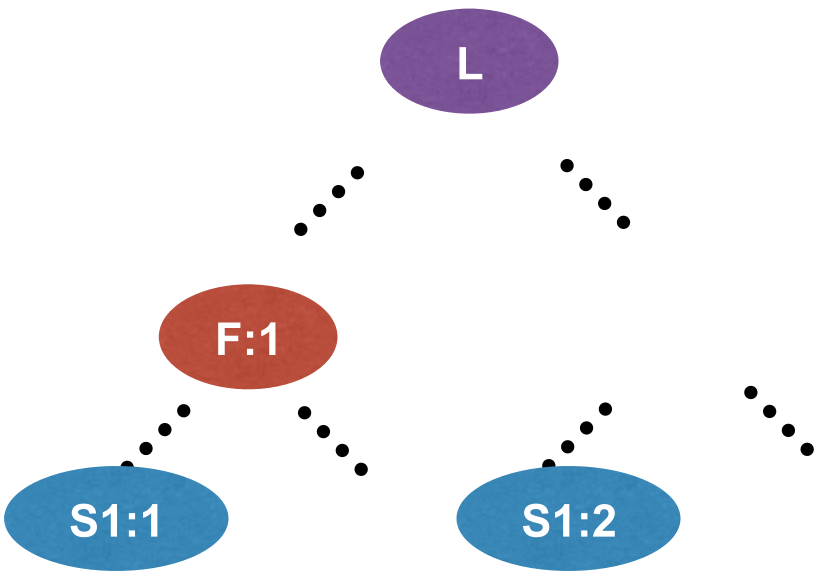
Overview of Our Approach



- **Extended ESP-Bags data race detector**
  - **Performs a sequential depth first execution of the program on a single processor**
- **Dynamic finish placement finds an optimal solution**
- **Static finish placement finds a heuristic solution**

Coupling Between Static and Dynamic Finish Placement

Dynamic Finish Placement



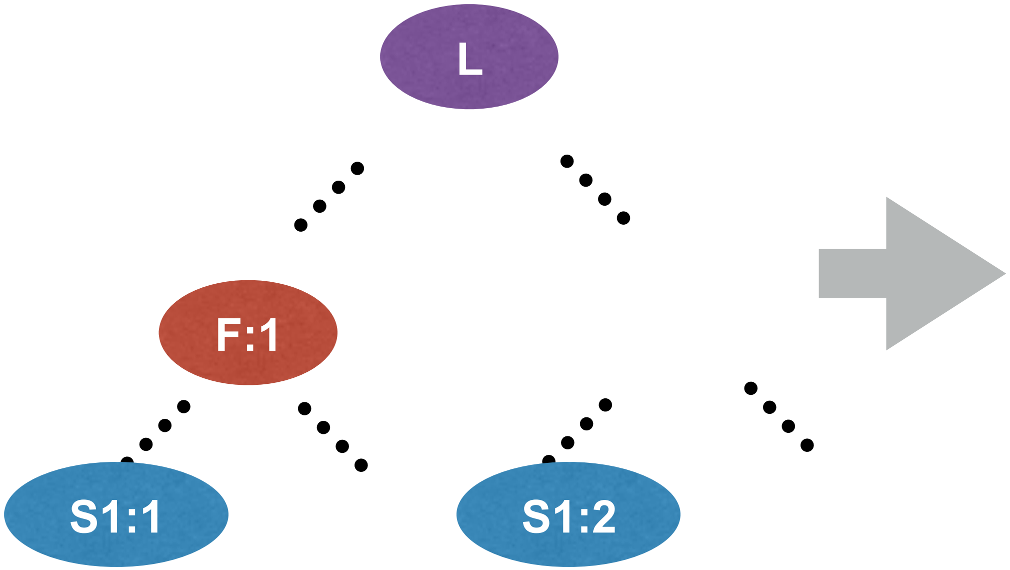
Insert finish nodes in S-DPST

Static Finish Placement

```
public static void main (...) {
            ...
            S1; ...
            ...
}
```

Coupling Between Static and Dynamic Finish Placement

Dynamic Finish Placement



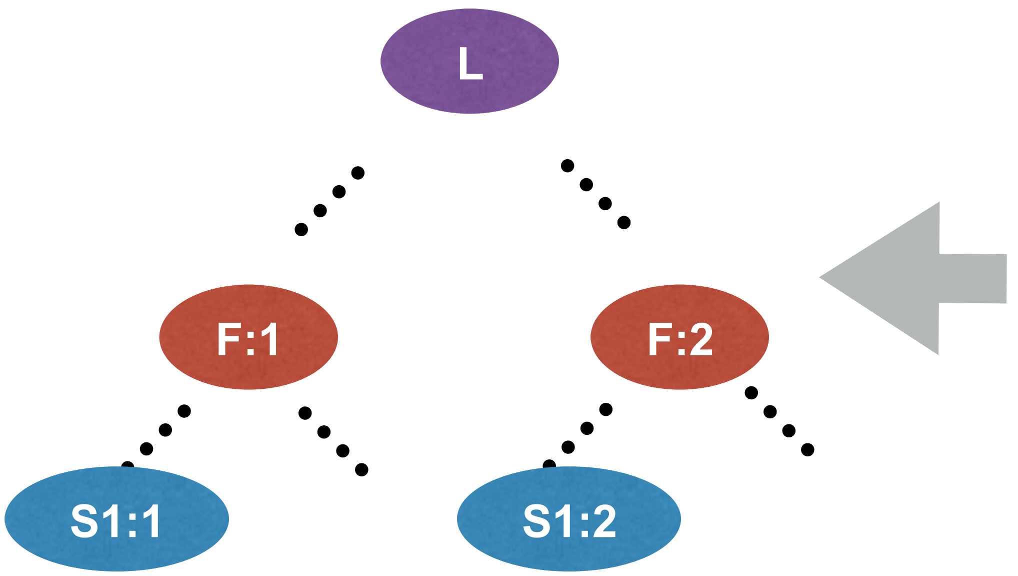
Static Finish Placement

```
public static void main (...) {
          ...
  finish { S1; ...}
          ...
}
```

Dynamic to static finish mapping

Coupling Between Static and Dynamic Finish Placement

Dynamic Finish Placement



Propagate finish back to S-DPST

Static Finish Placement

```
public static void main (...) {
        ...
  finish { S1; ...}
        ...
}
```

Program Repair Example: Quicksort

```
static void quicksort(int[] A, int M, int N) {
  if(M < N) {
     point p = partition(A, M, N);
     int I = p.get(0);
     int J =p.get(1);
     async quicksort(A, M, J);
     async quicksort(A, I, N);
   }
 }
...
quicksort(A, 0, size-1); //Call inside main
/* verify results */
```

Input program has data races

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Too much synchronization

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Best finish placement

Student Homework Evaluation

- Evaluated student homework submissions as part of an undergraduate course on parallel computing
- Week 1 Assignment: Perform manual repair of buggy quicksort program with missing finish constructs
- Compared 59 student submissions against the repair performed by the tool
  - 5 submissions had data races
  - 29 submissions were over-synchronized
  - 25 submissions matched the output from repair tool

Other Related Topics

- Determinism checking [SAS ‘10, WoDet ‘14]
- Deterministic reductions [WoDet ‘11, WoDet ’13]
- Definitions of Functional vs. Structural Determinism, Determinacy, Repeatability [DFM ’12]
- Delegated Isolation for Nested Task Parallelism [OOPSLA ‘11, OOPSLA ‘13]
- Object-based Isolation [EuroPar ‘15]
- Integrating Actors with Task Parallelism [OOPSLA ‘12, AGERE ‘14]
- Model Checking Task Parallel Programs using Gradual Permissions [ASE ’15]
- Analysis and Transformation of Parallel Programs [TOPLAS ’13, LCPC ‘15, PACT ’15]
- See Publications link in http://habanero.rice.edu

Conclusions

- New challenges for correctness and reliability in parallel software
  - Avoidance of parallelism/concurrency bugs
  - Detection of parallelism/concurrency bugs
  - Repair of parallelism/concurrency bugs
- Structured-parallel primitives can provide foundation for addressing these challenges
- This talk presented early experiences from the Habanero project, and key structured-parallel primitives that can enable effective avoidance, detection, and repair of parallel bugs