GRace: A Low-Overhead Mechanism for Detecting Data Races in GPU Programs

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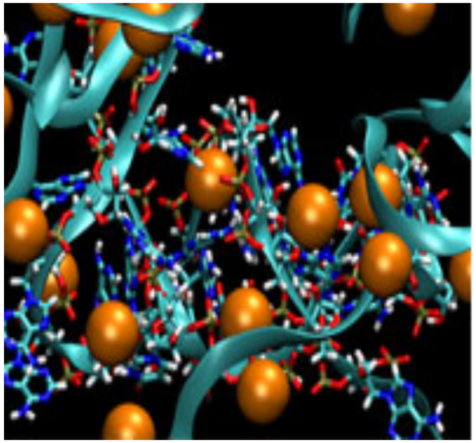
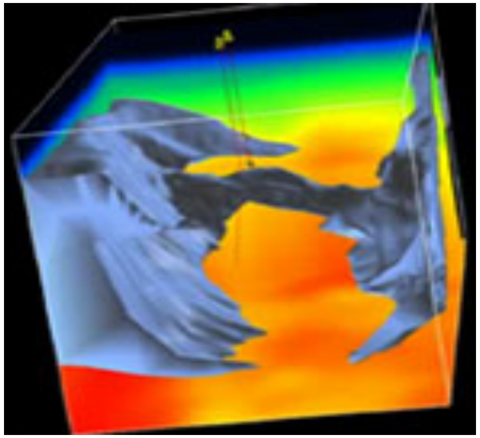
GPU Programming Gets Popular

- **Many domains are using GPUs for high performance**



GPU-accelerated Molecular Dynamics



GPU-accelerated Seismic Imaging

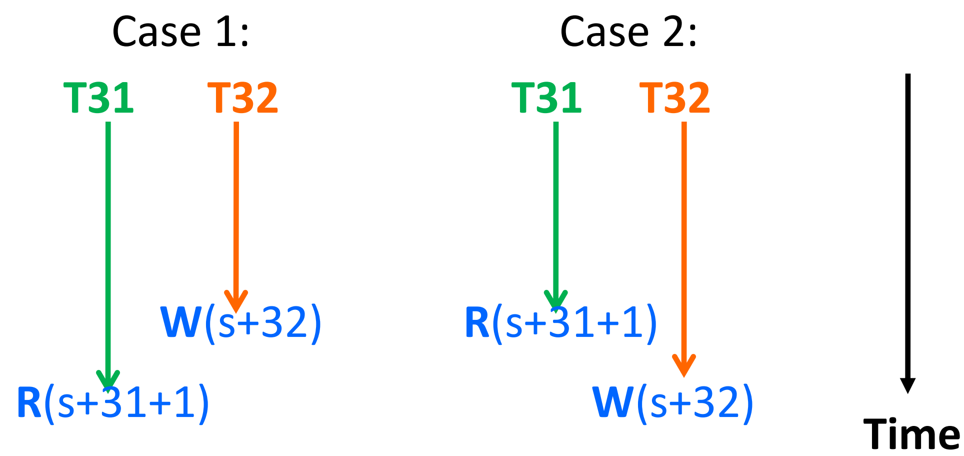
- **Available in both high-end/low-end systems**
  - **3** of the **top** 10 supercomputers were based on GPUs [Meuer+:10]
  - Many desktops and laptops are equipped with GPUs

Data Races in GPU Programs

- **A typical mistake**

```
1. __shared__  int s[];
2. int tid=threadIdx.x;

   …
3. s[tid] = 3; //W
4. result[tid] = s[tid+1] * tid; //R
   …
```



Result undeterminable!

- **May lead to severe problems later**
  - E.g. crash, hang, silent data corruption

Why Data Races in GPU Programs

- **In-experienced programmers**
  - GPUs are accessible and affordable to developers that never used parallel machines in the past

- **More and more complicated applications**
  - E.g. programs running on a cluster of GPUs involve other programming model like MPI (Message Passing Interfaces)

- **Implicit kernel assumptions broken by kernel users**
  - E.g. “max # of threads per block will be 256”,

    “initialization values of the matrix should be within a certain range”,

    Otherwise, may create overlapped memory indices among different threads

State-of-the-art Techniques

- **Data race detection for multithreaded CPU programs**
  - Lockset [Savage+:97] [Choi+:02]
  - Happens-before [Dinning+:90] [Perkovic+:96] [Flanagan+:09] [Bond+:10]
  - Hybrid [O'Callahan+:03][Pozninansky+:03][Yu+:05]

Inapplicable or unnecessarily expensive in barrier-based GPU programs ☹

- **Data race detection for GPU programs**
  - SMT(Satisfiability Modulo Theories)-based verification [Li+:10]

False positives & State explosion ☹

  - Dynamically tracking all shared-variable accesses [Boyer+:08]

False positives & Huge overhead ☹

Our Contributions

- **Statically-assisted dynamic approach**
  - Simple static analysis significantly reduces overhead
- **Exploiting GPU's thread scheduling and execution model**
  - Identify key difference between data race on GPU/CPU
  - Avoid false positives
- **Making full use of GPU's memory hierarchy**
  - Reduce overhead further

Precise: no false positives in our evaluation

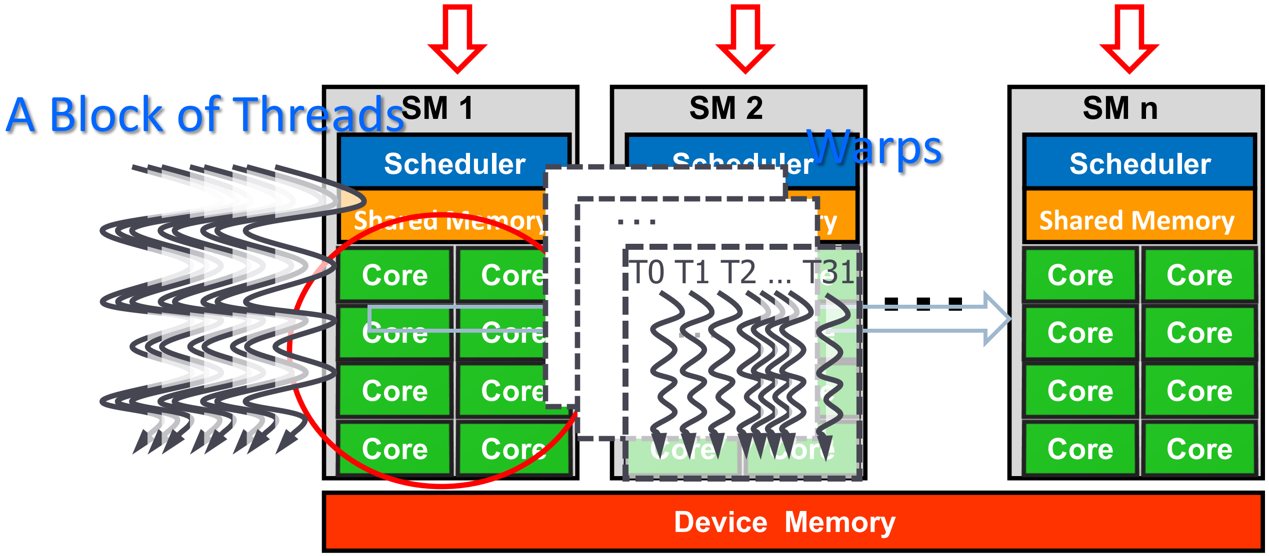
Low-overhead: as low as 1.2x on real GPU

Outline

- Motivation
- **What's new in GPU programs**
- GRace
- Evaluation
- Conclusions

Execution Model

- **GPU architecture and SIMT(Single-Instruction Multiple-Thread)**



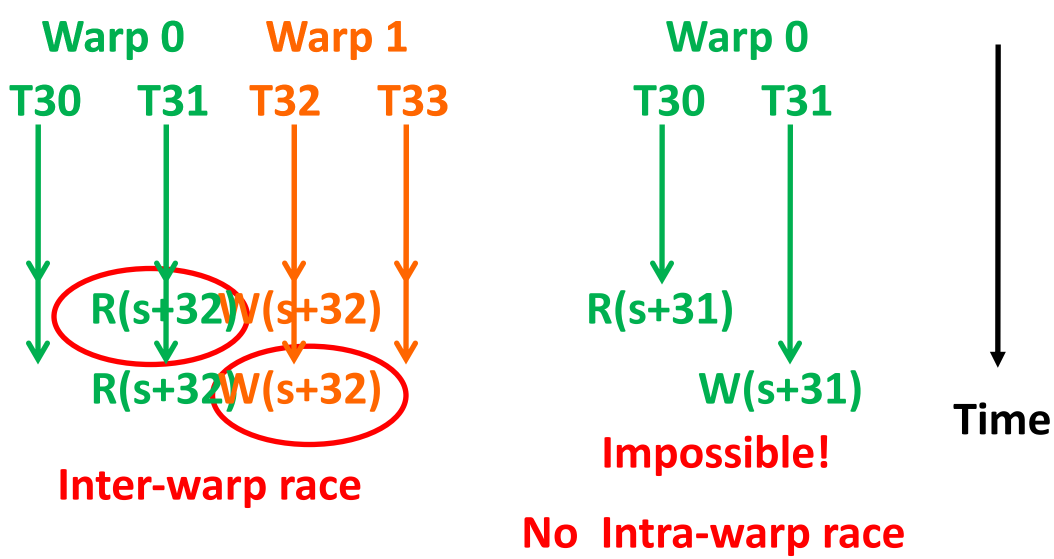
- Streaming Multiprocessors (SMs) execute blocks of threads
- Threads inside a block use barrier for synchronization
- A block of threads are further divided into groups called **Warps**
  - 32 threads per warp
  - Scheduling unit in SM

Our Insights

Two different types of data races between barriers

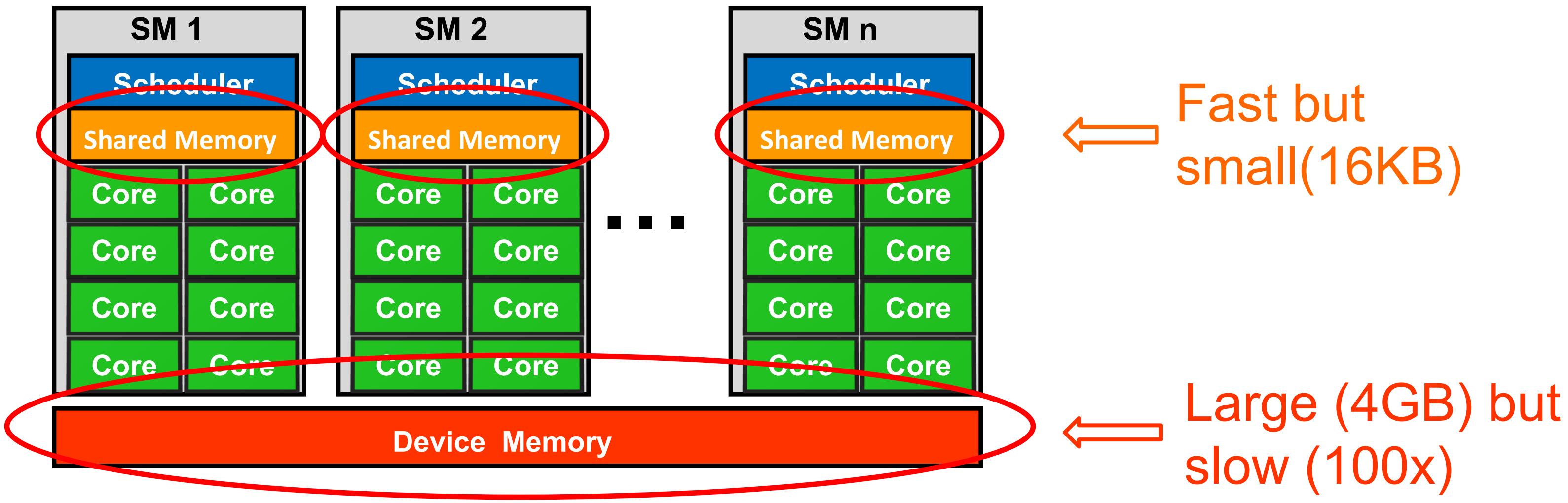
- **Intra-warp races**
  - Threads within a warp can only cause data races by executing the same instruction
- **Inter-warp races**
  - Threads across different warps can have data races by executing the same or different instructions

```
1. __shared__  int s[];
2. int tid=threadIdx.x;
   …
3. s[tid] = 3; //W
4. result[tid] = s[tid+1] * tid; //R
   …
```



Memory Hierarchy

- **Memory constraints**



- **Performance-critical**
  - Frequently accessed variables are usually stored in shared memory
  - Dynamic tool should also try to use shared memory whenever possible

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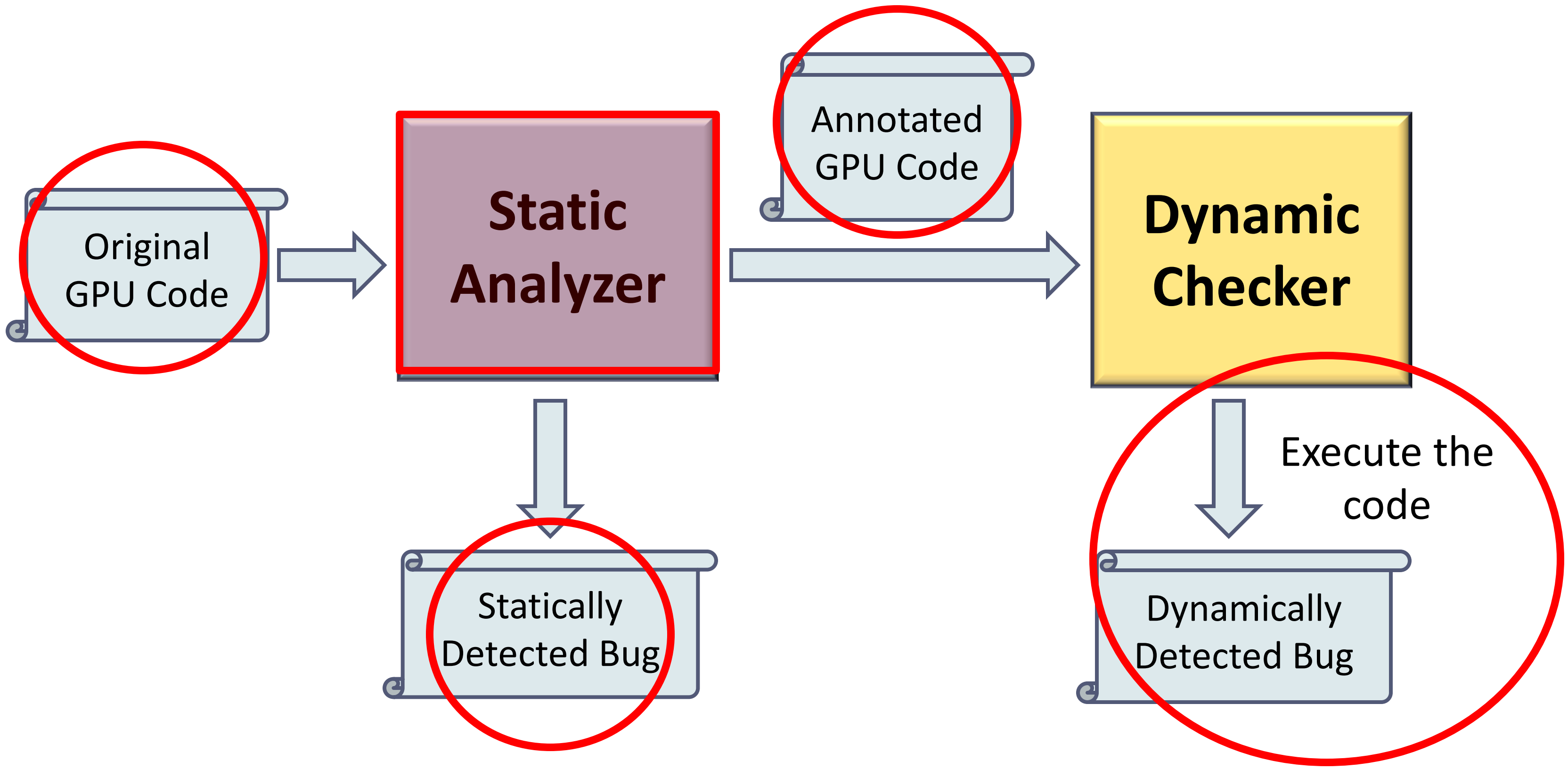
GRace: Design Overview

- **Statically-assisted dynamic analysis**



Simple Static Analysis Helps A Lot

- **Observation I:**
  - Many conflicts can be easily determined by static technique

```
1. __shared__  int s[];
2. int tid=threadIdx.x;
   …
3. s[tid] = 3; //W
4. result[tid] = s[tid+1] * tid; //R
   …
```

tid: 0 ~ 511

W(s[tid]): (s+0) ~ (s+511)

R(s[tid+1]): (s+1) ~ (s+512)

Overlapped!

❶ Statically detect certain data races &

❷ Prune memory access pairs that cannot be involved in data races

Static analysis can help in other ways

- **How about this…**

```
__shared__ float s[];
…
for(r=0; …; …)
{ …
  for(c=0; …; …)
  { …
    temp = s[input[c]];//R
  }
}
```

- **Observation II:**
  - Some accesses are loop-invariant

R(s+input[c]) is irrelevant to **r**

Don’t need to monitor in every **r** iteration

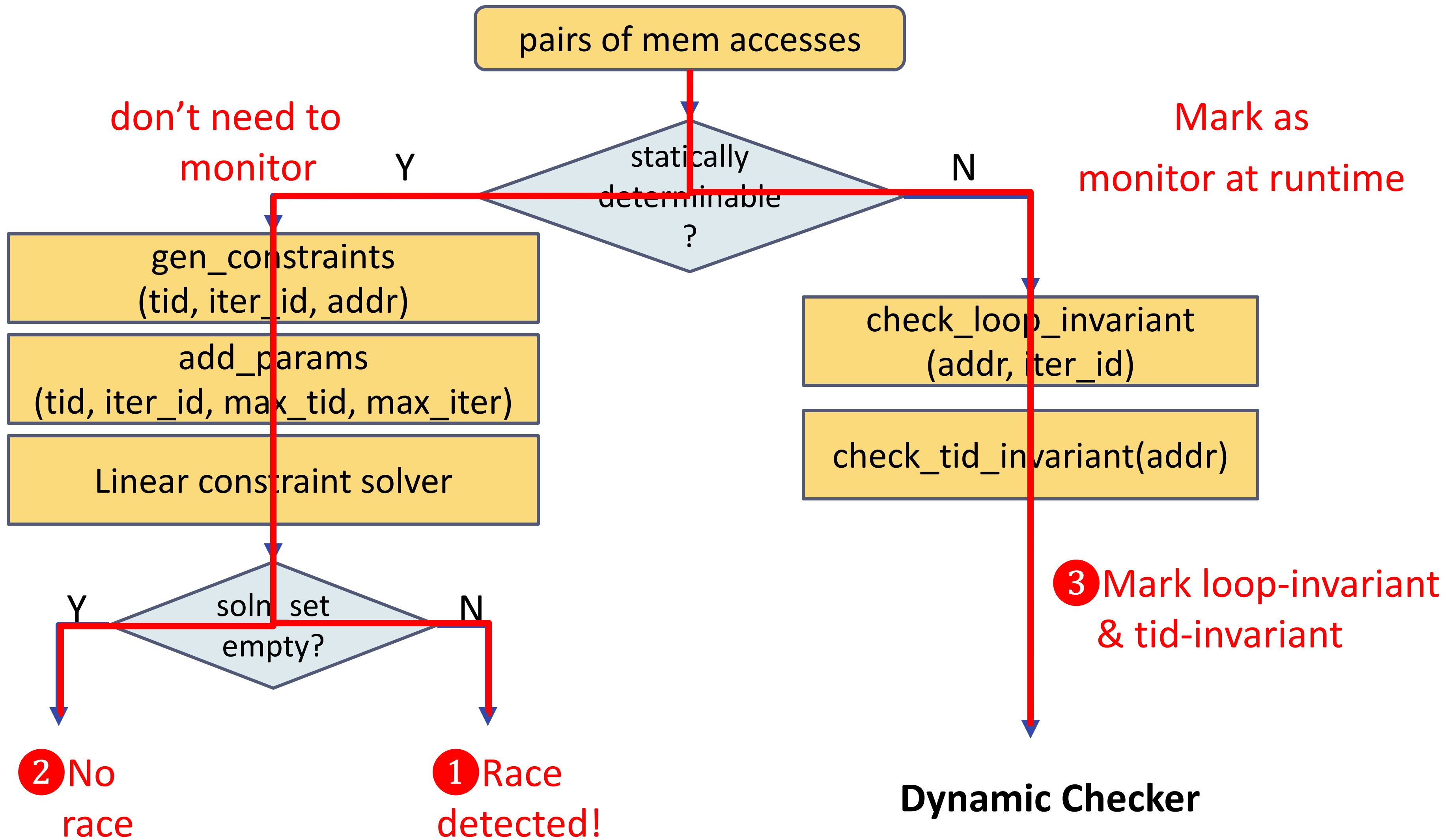
- **Observation III:**
  - Some accesses are tid-invariant

R(s+input[c]) is irrelevant to **tid**

Don’t need to monitor in every thread

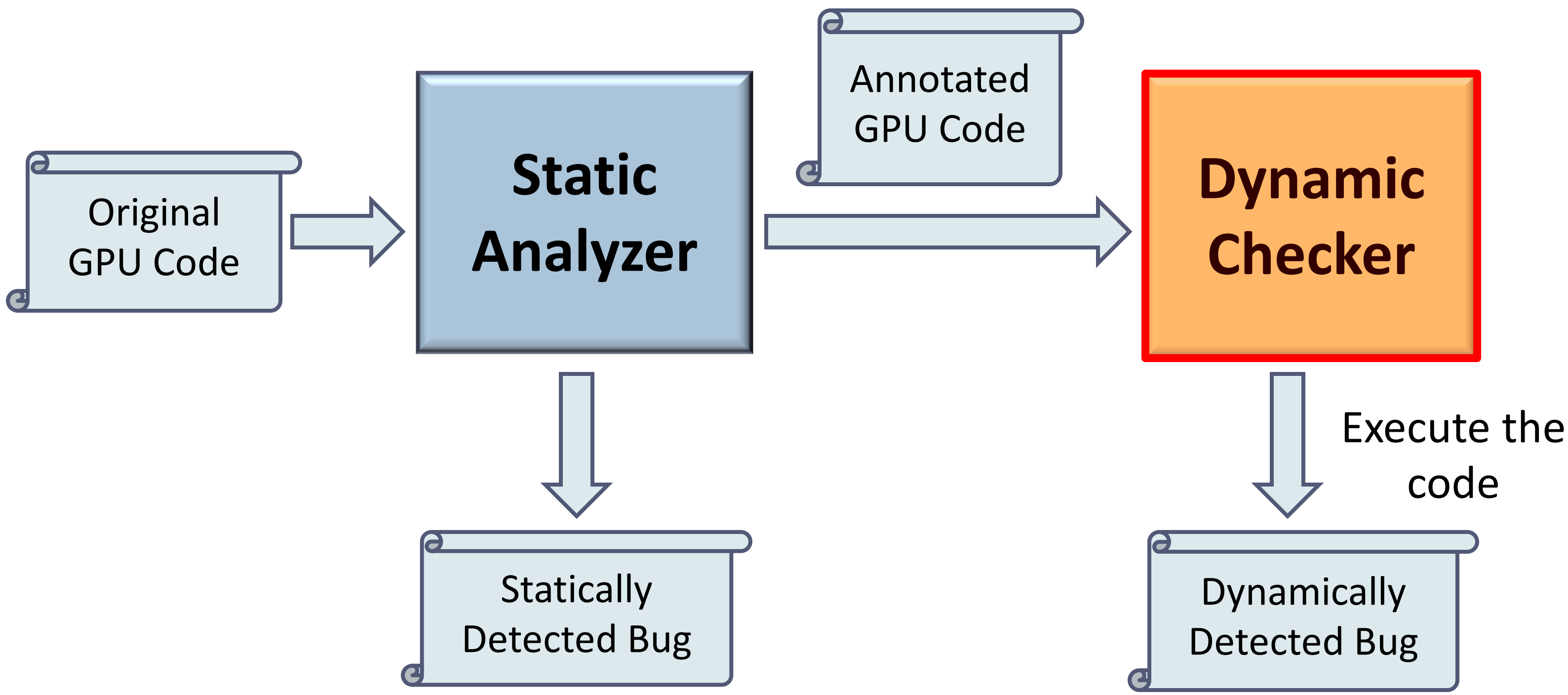
❸ Further reduce runtime overhead by identifying loop-invariant & tid-invariant accesses

Static Analyzer: Workflow



GRace: Design Overview

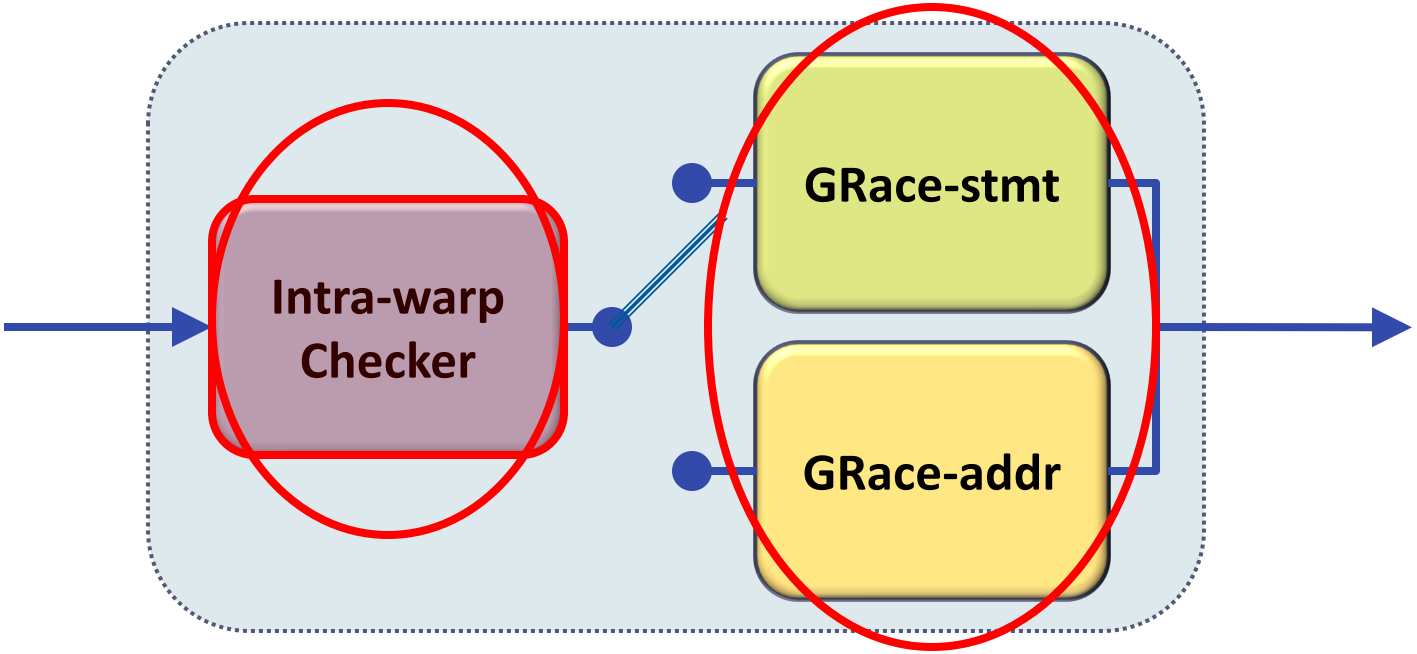
- **Statically-assisted dynamic analysis**



Dynamic Checker

Reminder:

- **Intra-warp races**: **caused by threads within a warp**
- **Inter-warp races**: **caused by threads across different warps**

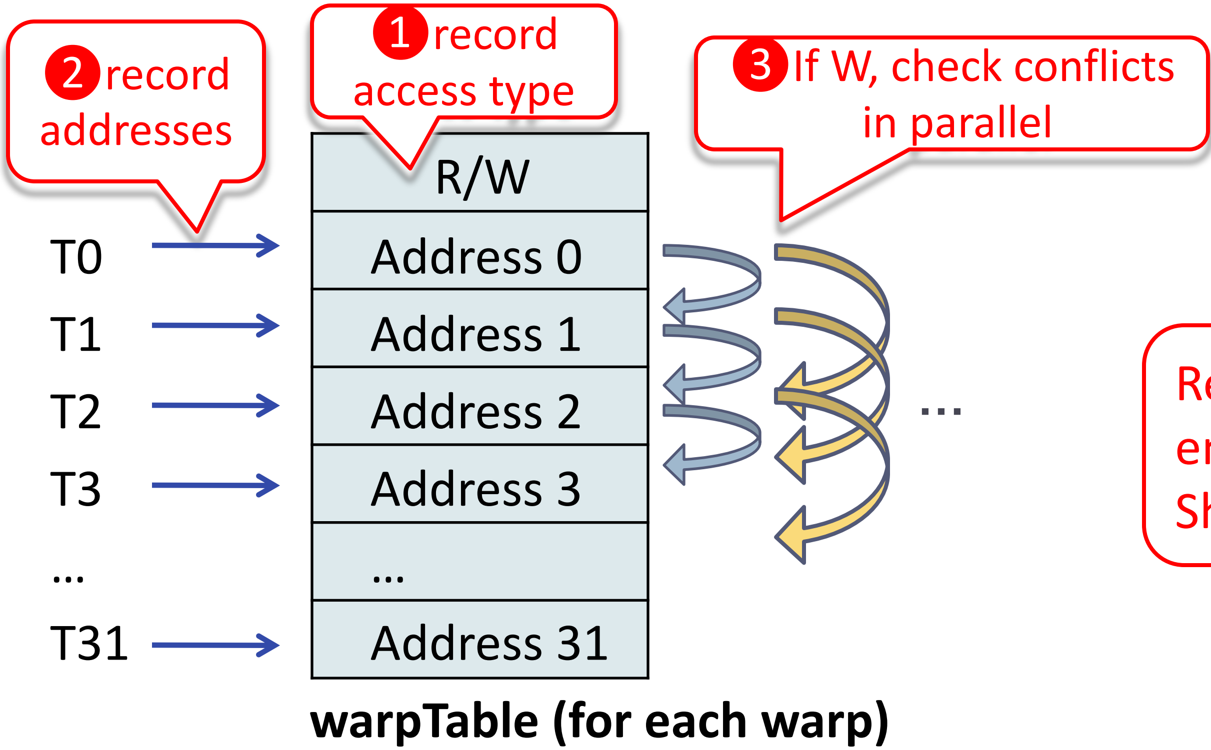


Check **Intra-warp** data races

Check **Inter-warp** data races:
Two design choices with diff. trade-offs

Intra-warp Race Detection

- **Check conflicts among the threads within a warp**
  - Perform detection immediately after each monitored memory access



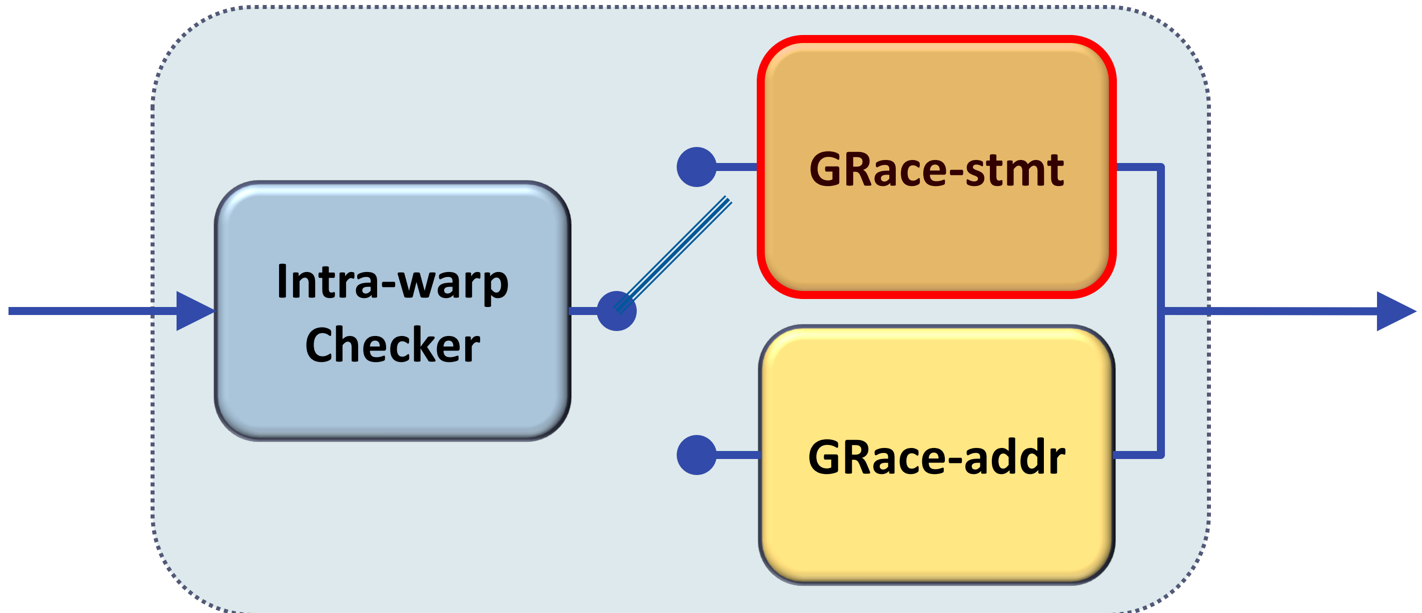
Recyclable and small enough to reside in Shared Memory

Fast & Scalable ✓

Dynamic Checker

Reminder:

- **Intra-warp races: caused by threads within a warp**
- **Inter-warp races: caused by threads across different warps**

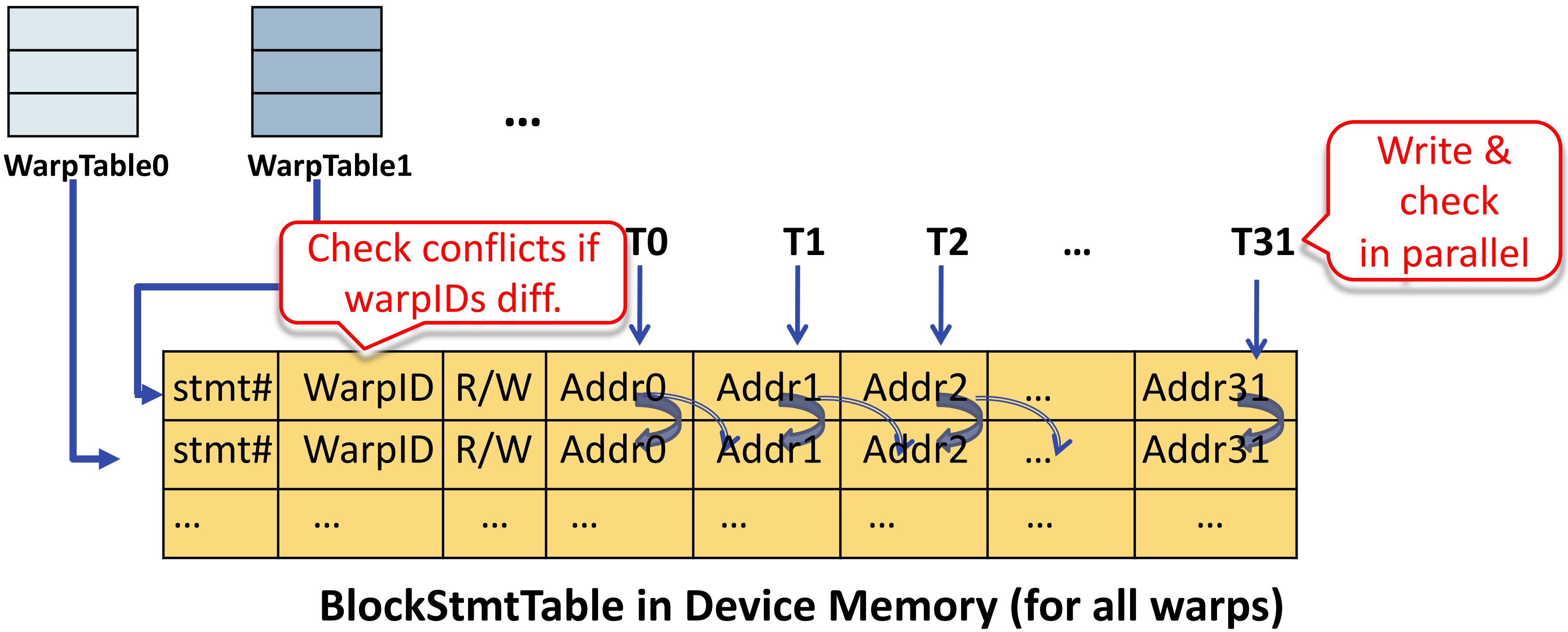


Check **Intra-warp** data races in Shared Memory

Check **Inter-warp** data races: Two design choices with diff. trade-offs

GRace-stmt: Inter-warp Race Detection I

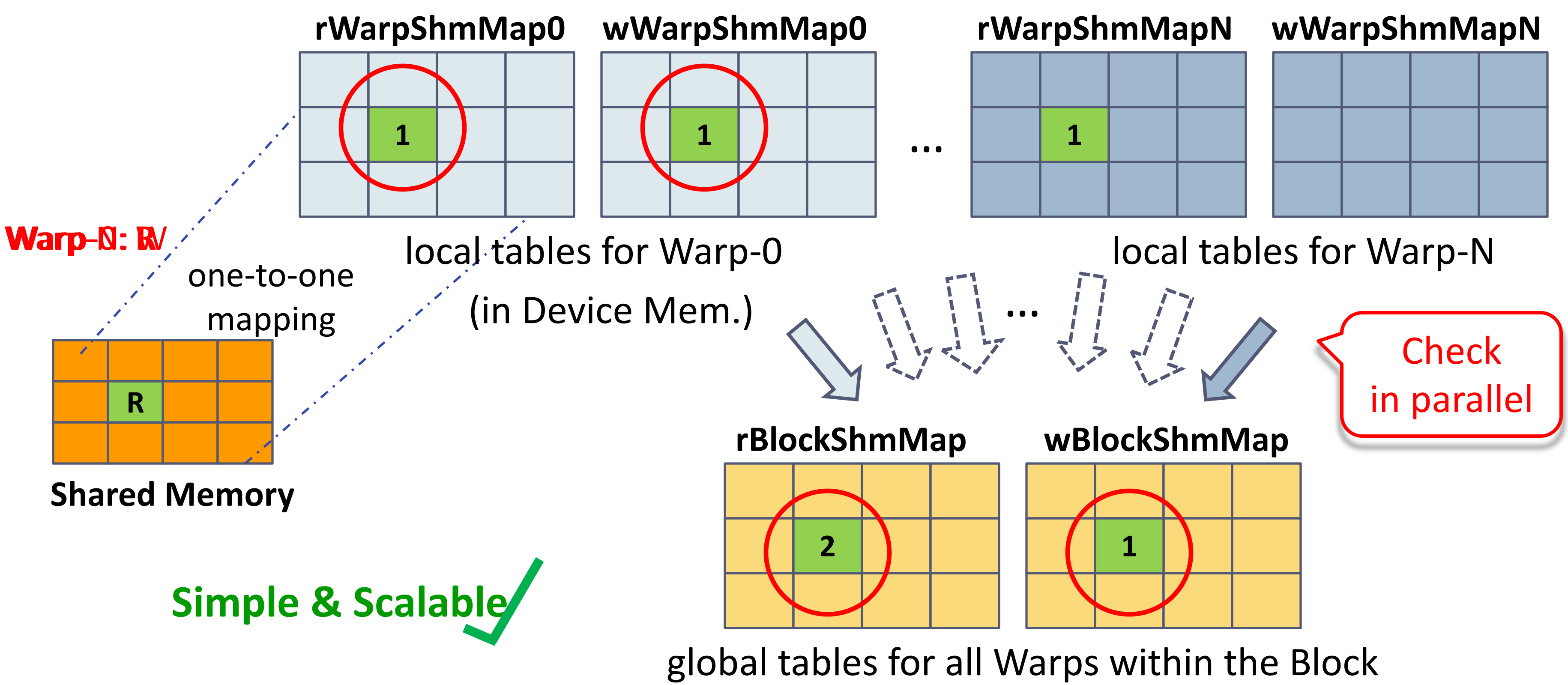
- **Check conflicts among the threads from different warps**
  - After each monitored mem. access, record info. to BlockStmtTable
  - At synchronization call, check conflicts between diff. warps



Accurate diagnostic info. ✓

GRace-addr: Inter-warp Race Detection II

- **Check conflicts among the threads from different warps**
  - After each monitored mem access, update corresponding counters
  - At synchronization call, infer races based on local/global counters



Simple & Scalable

Outline

- Motivation
- What's new in GPU programs
- GRace
  - Static analyzer
  - Dynamic checker
- **Evaluation**
- Conclusions

Methodology

- **Hardware**
  - **GPU**: NVIDIA Tesla C1060
    - 240 cores (30×8), 1.296GHz
    - 16KB shared memory per SM
    - 4GB device memory
  - CPU: AMD Opteron 2.6GHz ×2
  - 8GB main memory
- **Software**
  - Linux kernel 2.6.18
  - CUDA SDK 3.0
  - PipLib (Linear constraint solver)
- **Applications**
  - co-cluster, em, scan

Overall Effectiveness

- Accurately report races in three applications
- No false positives reported

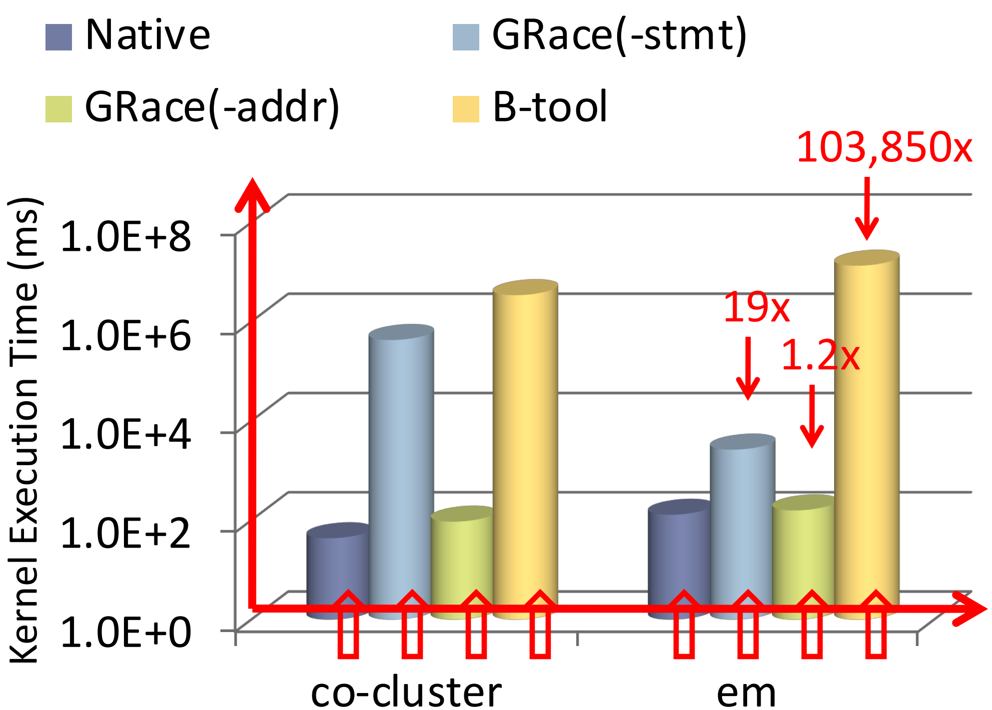
Apps	GRace(W/-stmt)				GRace(W/-addr)		
	R-Stmt#	R-Mem#	R-Thd#	FP#	R-Mem#	R-Wp#	FP#
co-cluster	1	10	1,310,720	0	10	8	0
em	14	384	22,023	0	384	3	0
scan	3 pairs of racing statements are detected by Static Analyzer						

R-Stmt: pairs of conflicting accesses
R-Mem: memory addresses invoked in data races
R-Thd: pairs of racing threads
R-Wp: pairs of racing warps
FP: false positive
RP: race number reported by B-tool

Apps	B-tool	
	RP#	FP#
co-cluster	1	0
em	200,445	45,870
scan	Error	

Runtime Overhead

- GRace(W/-addr): very modest
- GRace(W/-stmt): higher overhead with diagnostic info. , but still faster than previous tool



Is there any data race in my kernel?

GRace-addr can answer quickly

Where is it?

GRace-stmt can tell exactly

Benefits from Static Analysis

- Simple static analysis can significantly reduce overhead

Apps	Without Static Analyzer		With Static Analyzer	
	Stmt	MemAcc	Stmt	MemAcc
co-cluster	10,524,416	10,524,416	41,216	41,216
em	19,070,976	54,460,416	20,736	10,044

Execution # of monitored statements and memory accesses

Stmt: statements

MemAcc: memory access

Conclusions and Future Work

- **Conclusions**
  - Statically-assisted dynamic analysis
  - Architecture-based approach: Intra/Inter–warp race detection
  - Precise and Low-overhead
- **Future work**
  - Detect races in device memory
  - Rank races

Thanks!