Lightweight Fault Detection in Parallelized Programs

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Program Parallelization

- Parallelism can be achieved via parallelization of sequential programs via easy-to-use *parallel constructs* → OpenMP, SpiceC [PPoPP'11], and TBB.

- Data Dependence Related Concurrency Bugs
  - Data races
  - Atomicity violations

Comparison Checking

- Conventional [PACT'98] [FSE'99]
  - Locate program faults by leveraging the availability of *two versions* of a program – one supposed *correct* version and one *derived* version
- In Our Scenario
  - A sequential version ***S*** and a parallelized version ***P***
  - Faulty parallelization → data dependence violation
    - Data dependences enforced by *S* are not preserved by *P*

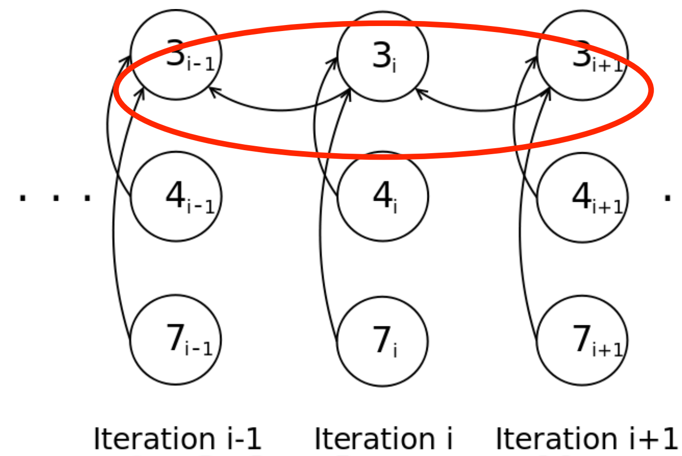
Debugging *Parallelized* Programs

Basic Idea:

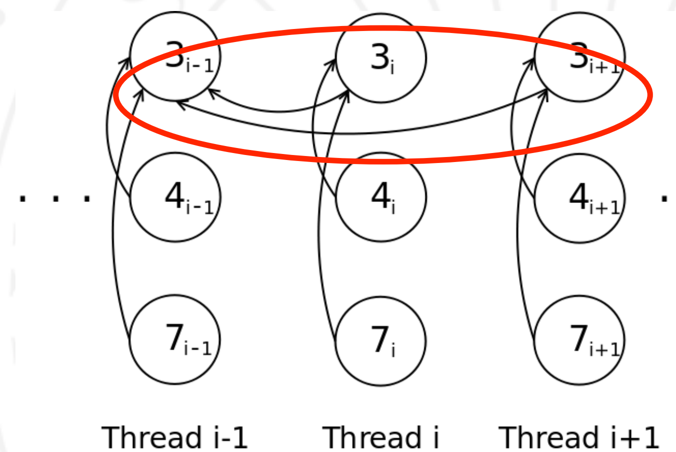
- Comparison check the data dependences exercised by the executions of ***S*** and ***P***
  - dynamic *D*ata *D*ependence *G*raphs:*sDDG*+*pDDG*
    - Nodes: execution instances of statements
    - Edges: data dependences between nodes
  - Faulty parallelization: *different* sDDG and pDDG constructed using the *same* input

Data Race Detection

```
1: #pragma omp parallel for
2: for (;;) {
       #pragma omp critical
3:     if (fgets(s, NUM, stdin) == NULL) break;
4:     if (s[0] == '!') {
5:         /* Other relevant code here */
6:     }
7:     if (!separate_sentence(s)) {
8:         /* Other relevant code here */
9:     }
10: }
```



sDDG



pDDG

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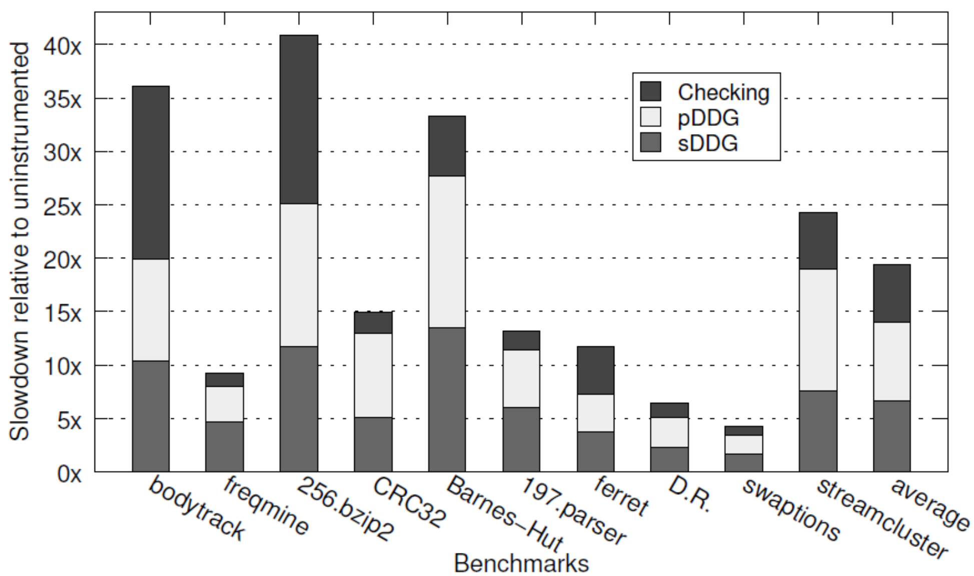
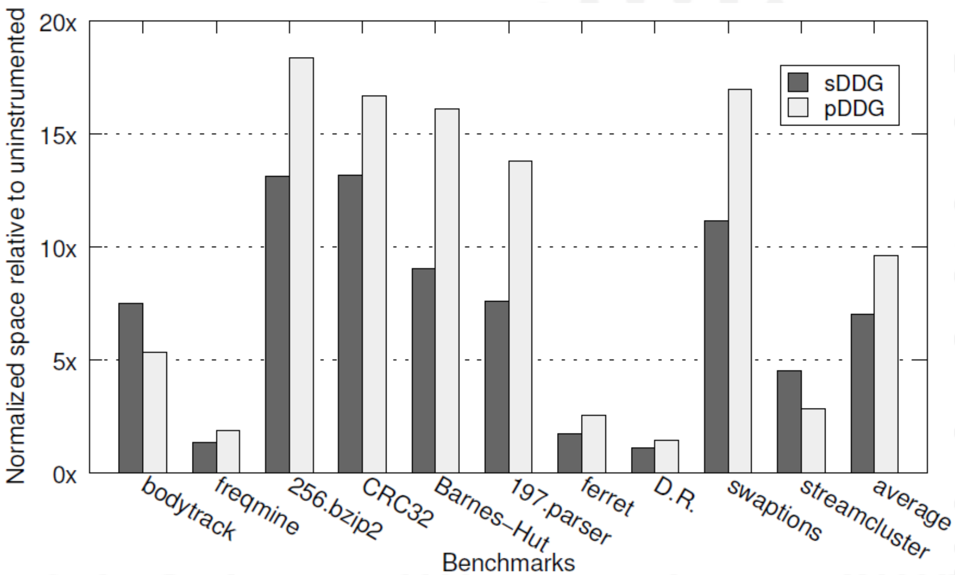
Limitations

- DDG Construction Overhead



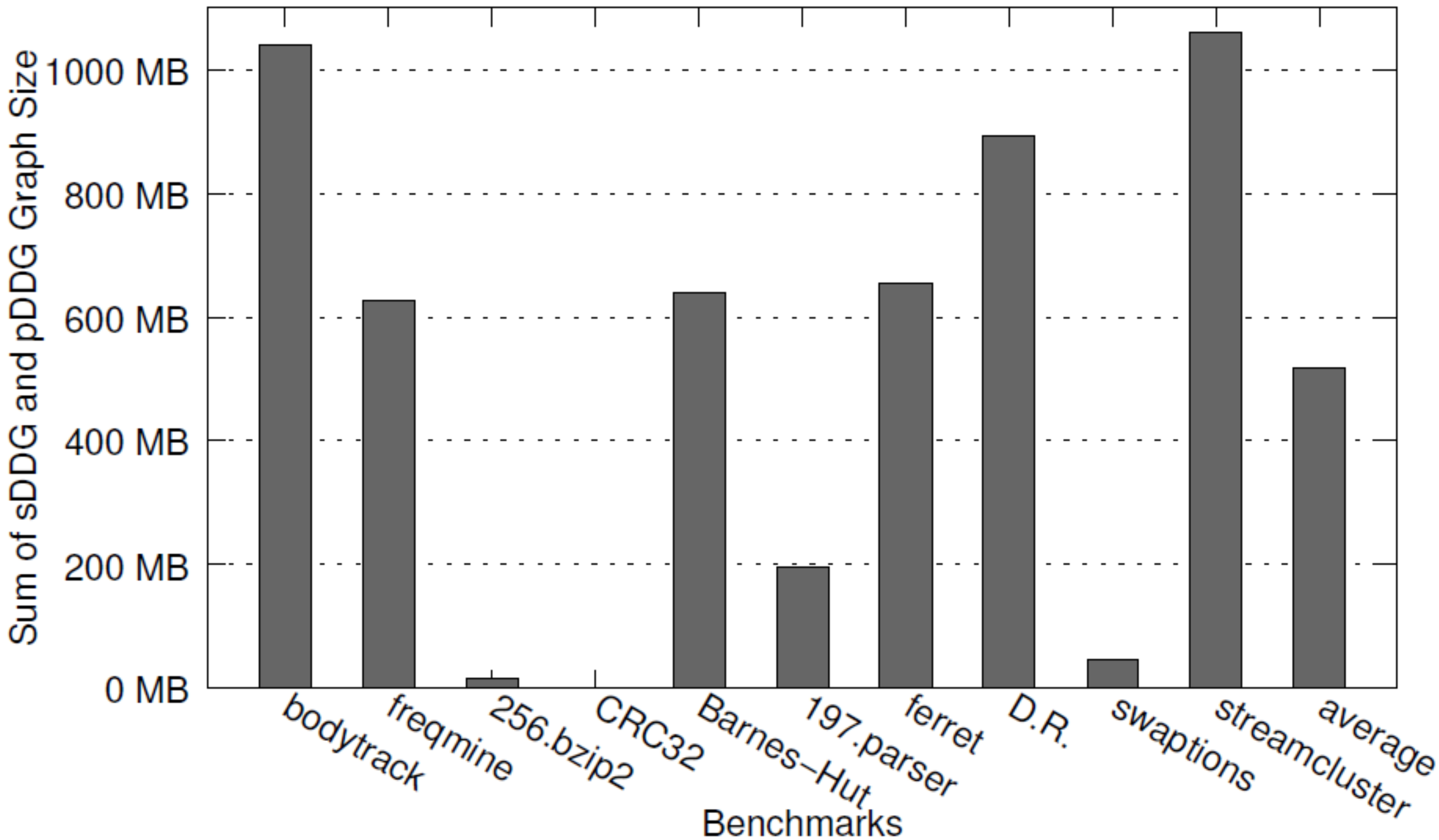
Execution Time



Memory Space

Limitations (Cont.)

- Graph Size and Checking Time



Limitations (Cont.)

- Dependence Violation May Not Occur
  - *Not every* interleaving causes violation
  - As low as 10% chance to expose a data race; up to 22 hours to expose an atomicity violation [ASPLOS'09]
- Validity of Comparing Two Runs
  - *Random numbers* alter control flow [ISSTA'07]
  - Inconsistency ≠ a concurrency bug

Significant limitations…
How can we get rid of them?

OPT-1: Region Graphs

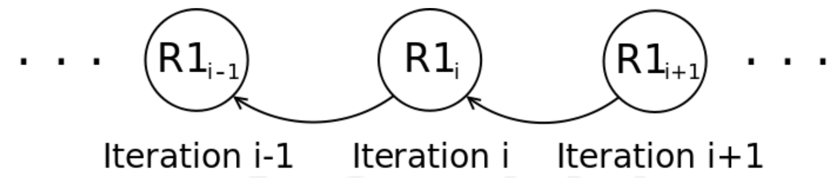
- Eliminate *irrelevant* dependences
  - Data dependences in sequentially executed code
  - ***Savings***: time + space for tracking and checking

- *fine*-grained graphs → *coarse*–grained graphs
  - Statements (DDG) → Code regions (DRG)
  - ***Savings***: graph size

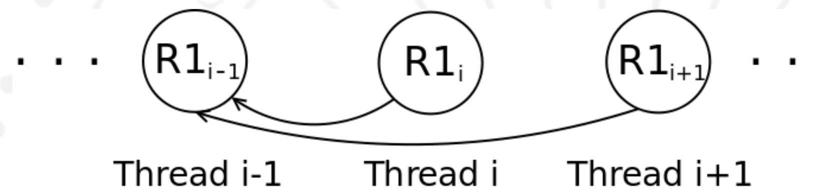
OPT-1: Region Graphs (Cont.)

```
#pragma omp parallel for
for (;;) {
    if (fgets(s, NUM, stdin) == NULL) break;
    if (s[0] == '!') {
        /* Other relevant code here */
    }
    if (!separate_sentence(s)) {
        /* Other relevant code here */
    }
}
```

Region *R1*



sDRG



pDRG

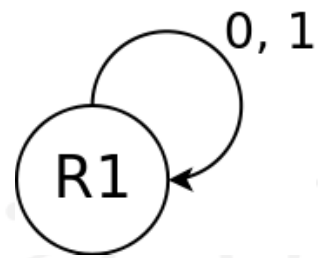
/ the same data race example... */*

OPT-2: Summarize Region Instances

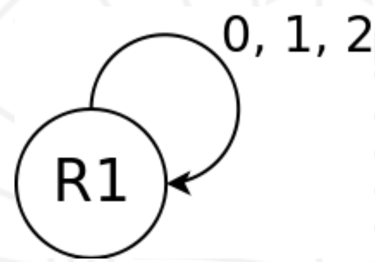
- A single node in a *DRG* represents all execution instances of a region
  - Different dependences need to be distinguished
  - ***Savings***: time for tracking and checking + graph size
- Annotate each edge by *dependence distances*
  - 0 indicates an *intra-iteration* dependence
  - A non-zero value indicates a *cross-iteration* dependence

OPT-2: Summarize Region Instances

```
#pragma omp parallel for
for (;;) {
    if (fgets(s, NUM, stdin) == NULL) break;
    if (s[0] == '!') {
        /* Other relevant code here */
    }
    if (!separate_sentence(s)) {
        /* Other relevant code here */
    }
}
```



sDRG '



pDRG '

/ the same data race example... */*

OPT-3: Static Region Graph

- Only the sequential version needs to be run
  - *Statically analyzing* the parallel constructs in the parallelized version
  - ***Savings***: time + space for tracking and checking

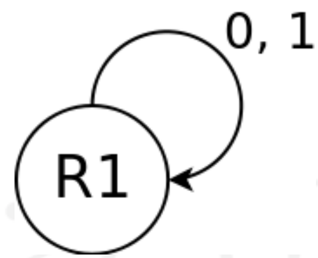
- Simplified concurrency bug detection
  - Check if data dependences *allowed* by OpenMP, SpiceC, and TBB *violate* sequential semantics
  - ***Eliminate the limitations***:
    - Reproducibility rate + validity of comparing two runs

OPT-3: Static Region Graph (Cont.)

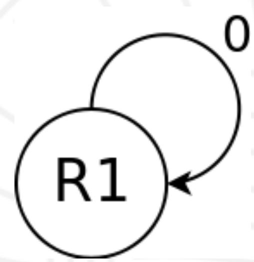
Construct	Allowed Dependences
OpenMP	
parallel [for|do]	Intra-iteration dependences
section	Intra-iteration dependences
critical	Intra-iteration/cross-iteration dependences
ordered	Intra-iteration/cross-iteration dependences
SpiceC	
doall	Intra-iteration dependences
doacross	Intra-iteration dependences
pipelining	Intra-iteration/cross-iteration dependences
after(ITER-x, R_y)	Intra-iteration/cross-iteration dependences from region R_y to current region with a distance x
atomicity_check	Intra-iteration/cross-iteration dependences
TBB	
parallel_for	Intra-iteration dependences
parallel_reduce	Intra-iteration dependences and cross-iteration dependences of join
parallel_scan	Intra-iteration dependences and cross-iteration dependences of reverse_join
parallel_pipeline	Intra-iteration dependences and cross-iteration dependences of filter

OPT-3: Static Region Graph (Cont.)

```
#pragma omp parallel for
for (;;) {
    if (fgets(s, NUM, stdin) == NULL) break;
    if (s[0] == '!') {
        /* Other relevant code here */
    }
    if (!separate_sentence(s)) {
        /* Other relevant code here */
    }
}
```



sDRG '



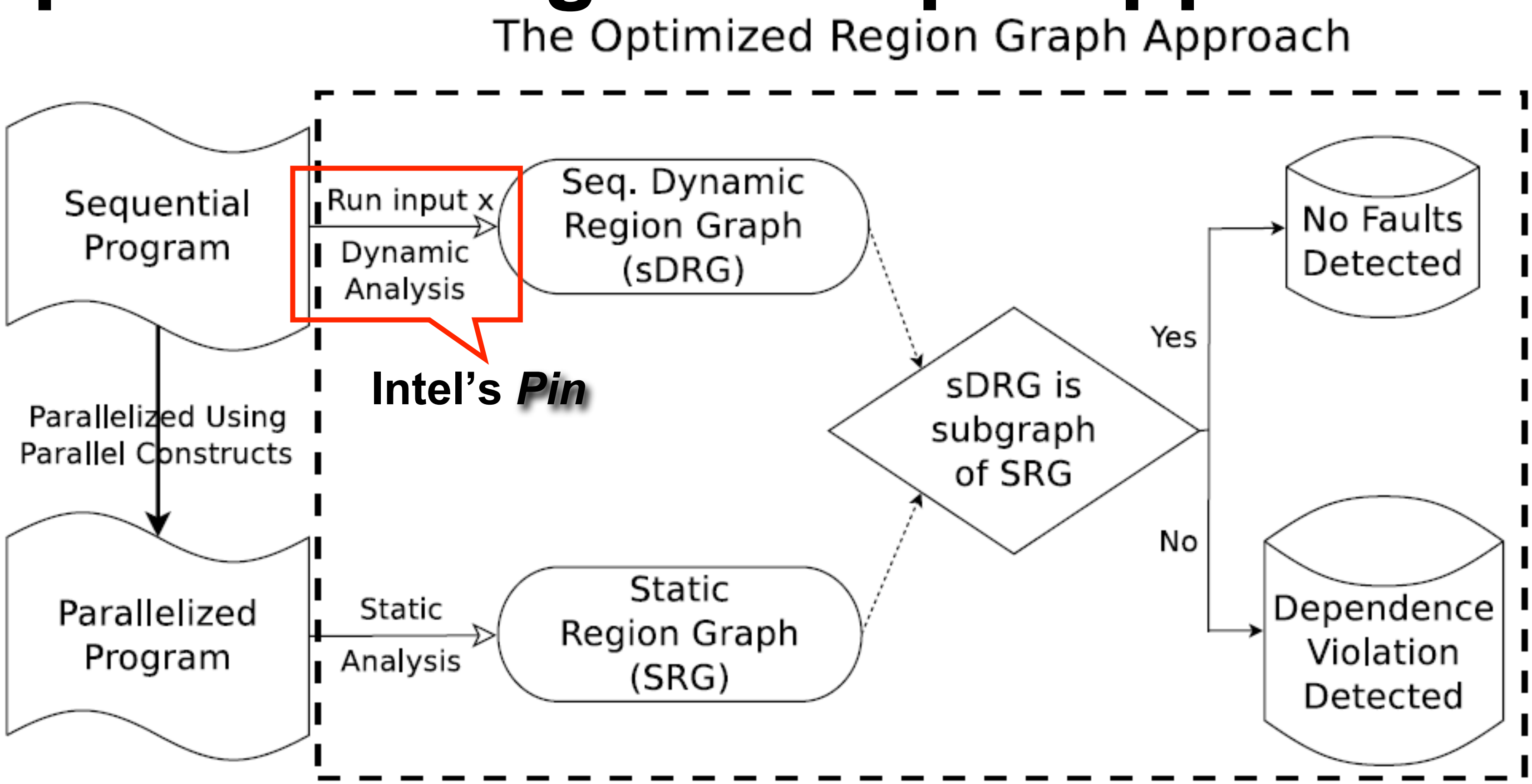
SRG

/ the same data race example… */*

Optimizing Comparison Checking

Optimization	Execution Time		Memory Space	
	Tracking	Checking	Tracking	Graph Size
OPT-1	√	√	√	√
OPT-2	√	√		√
OPT-3	√		√	

Optimized Region Graph Approach



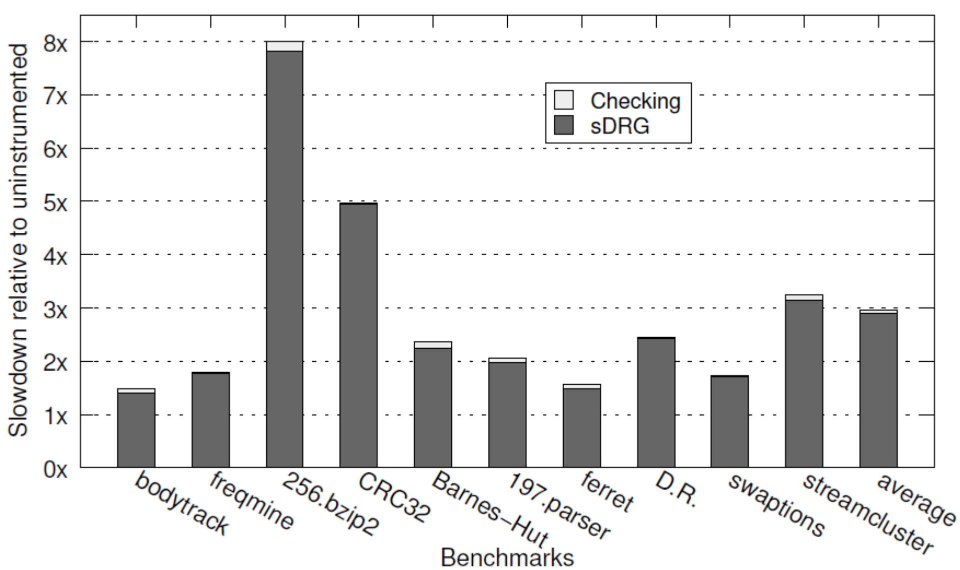
Observation: A dependence present in **sDRG**, but not allowed by **SRG**, represents *violation* against sequential program semantics by *parallelization* expressed by parallel constructs.

Evaluation

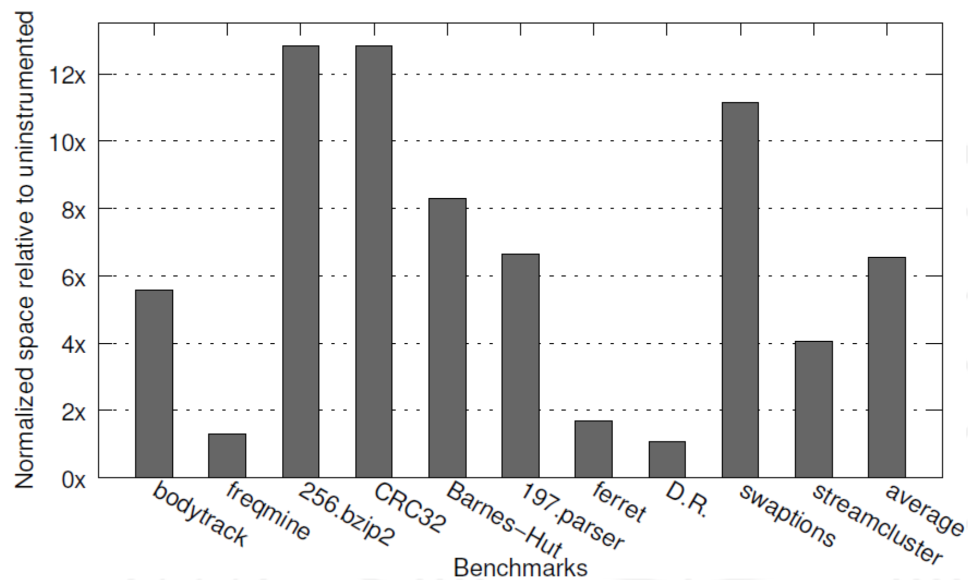
- Benchmarks
  - Applied our technique to ten benchmarks parallelized using OpenMP, SpiceC, and TBB
  - Selected from MiBench, SPEC CPU2000, Lonestar, and PARSEC benchmark suites

- Hardware Configuration
  - A 2.66 GHz Intel Core Duo DELL Dimension 9200 machine with 4 GB RAM
  - Linux kernel 2.6.32

sDRG Construction Overhead

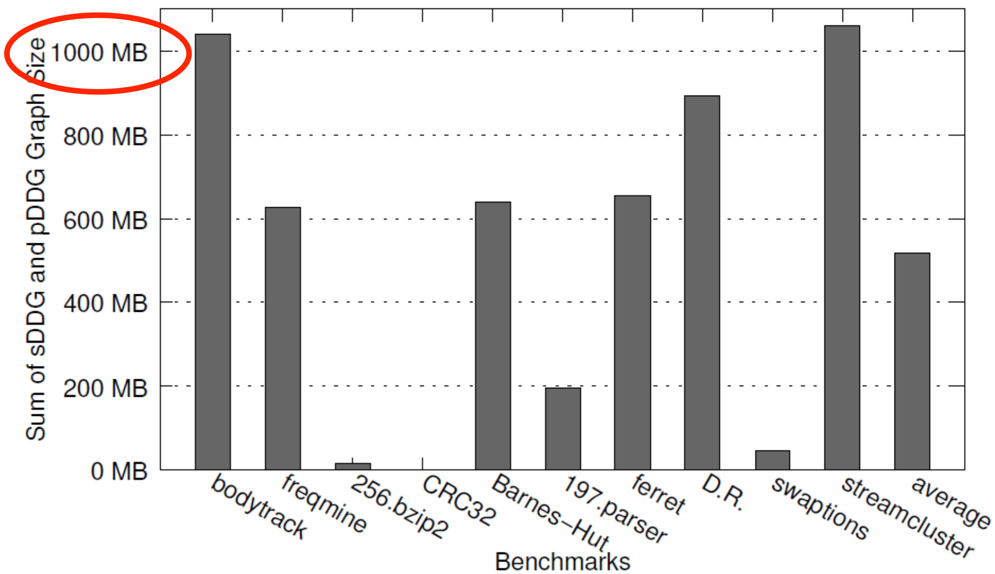


Execution Time

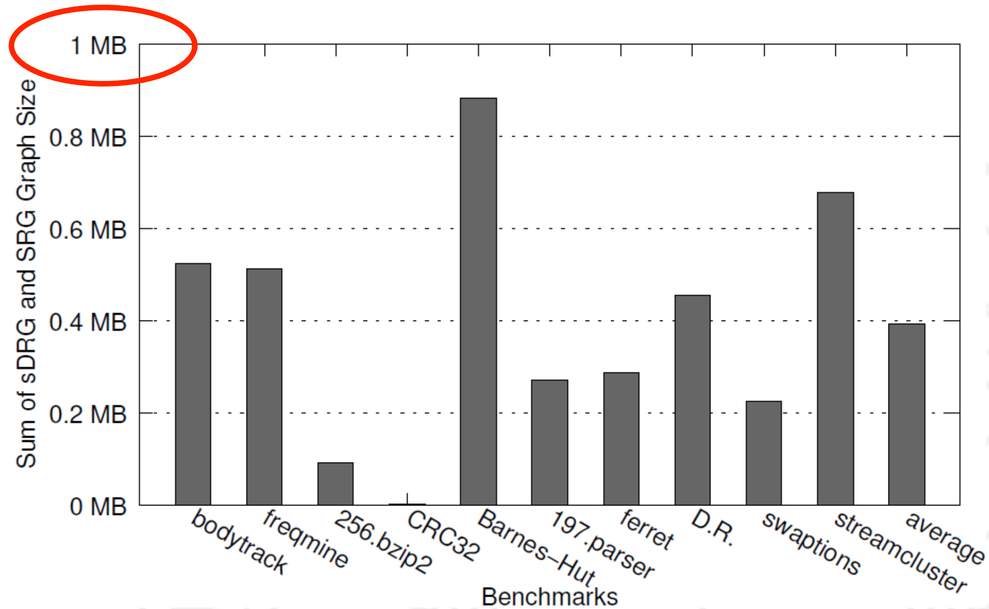


Memory Space

Graph Size Comparison



Previously



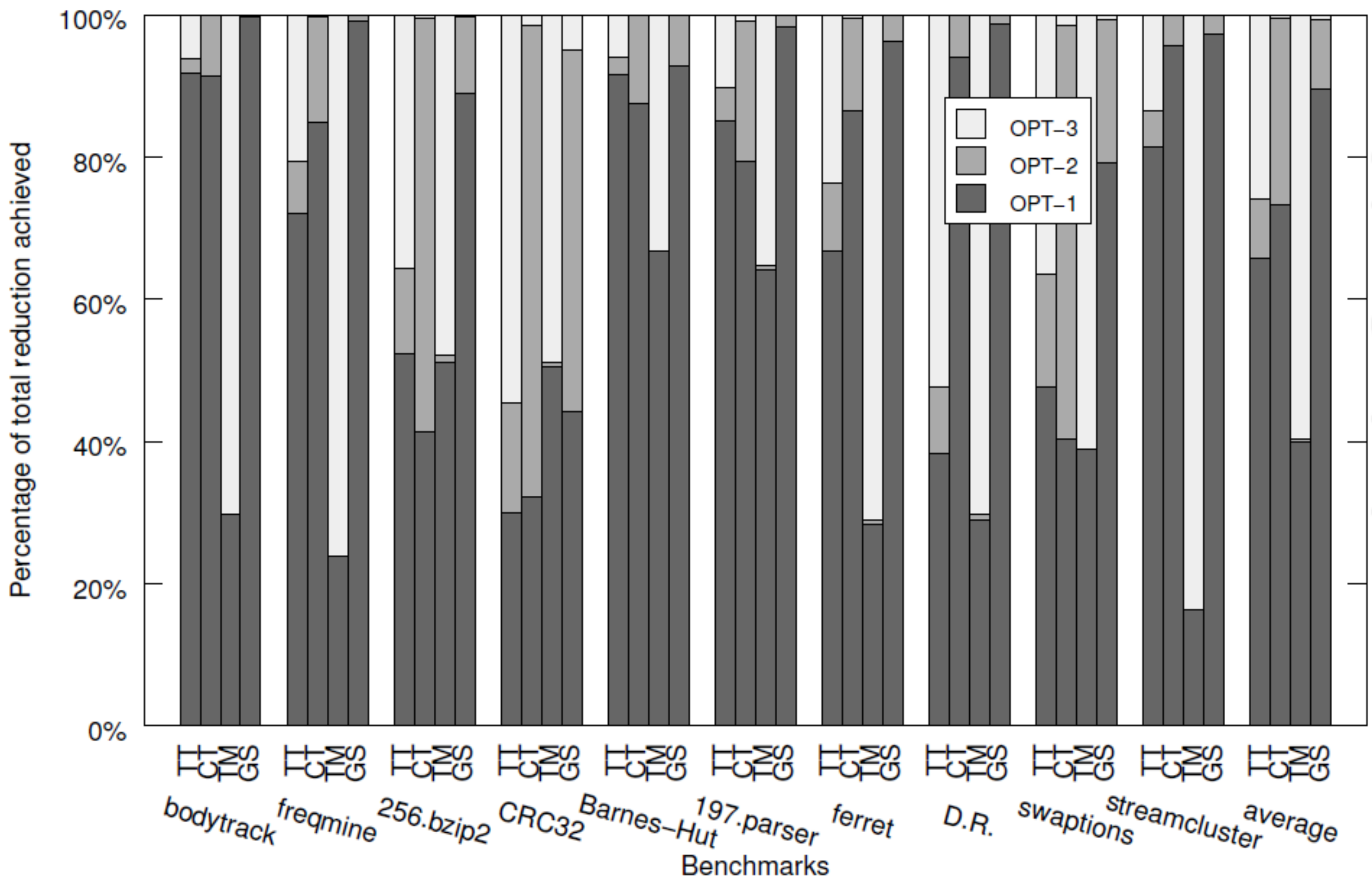
Now

Comparison of DRG and DDG

Cost of Using DRG as a Percentage of DDG

Benchmark	Execution Time		Memory Space	
	Tracking	Checking	Tracking	Graph Size
bodytrack	4.487%	0.371%	45.765%	0.049%
freqmine	14.416%	0.586%	51.985%	0.082%
256.bzip2	17.594%	0.623%	46.155%	0.584%
CRC32	22.854%	0.694%	47.240%	1.923%
Barnes-Hut	5.819%	1.519%	32.463%	0.139%
197.parser	9.474%	2.632%	34.419%	0.138%
ferret	12.713%	1.067%	33.196%	0.044%
DelaunayRefinement	33.483%	0.371%	71.006%	0.051%
swaptions	32.437%	1.976%	36.379%	0.494%
streamcluster	9.884%	1.282%	39.001%	0.064%
GeoMean	**13.463%**	**0.907%**	**42.534%**	**0.151%**

Breakdown of Overhead Reduction



Conclusions

- Debugging *Parallelized* Programs
  (OpenMP, SpiceC, and TBB)

  Versatility
  - Support for multiple types of concurrency bugs
  - Support for multiple parallel programming models

  Novelty
  - No requirement for execution of parallel programs
  - Elimination of *reproducibility* and *validity* problems
  - Region level data dependence graphs
  - Only 3x slowdown on average