A Case for Parallelism Profilers and Advisers with What-If Analyses

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Is Parallel Programming Hard, And, If So, What Can You Do About It?

"Parallel programming has earned a reputation as one of the most difficult areas a hacker can tackle. Papers and textbooks warn of the perils of deadlock, livelock, race conditions, non-determinism, Amdahl's-Law limits to scaling, and excessive realtime latencies. And these perils are quite real; we authors have accumulated uncounted years of experience dealing with them, and all of the emotional scars, grey hairs, and hair loss that go with such experiences."

[McKenny:arXiv17]

Main reasons: use of the wrong abstraction, lack of performance analysis and debugging tools

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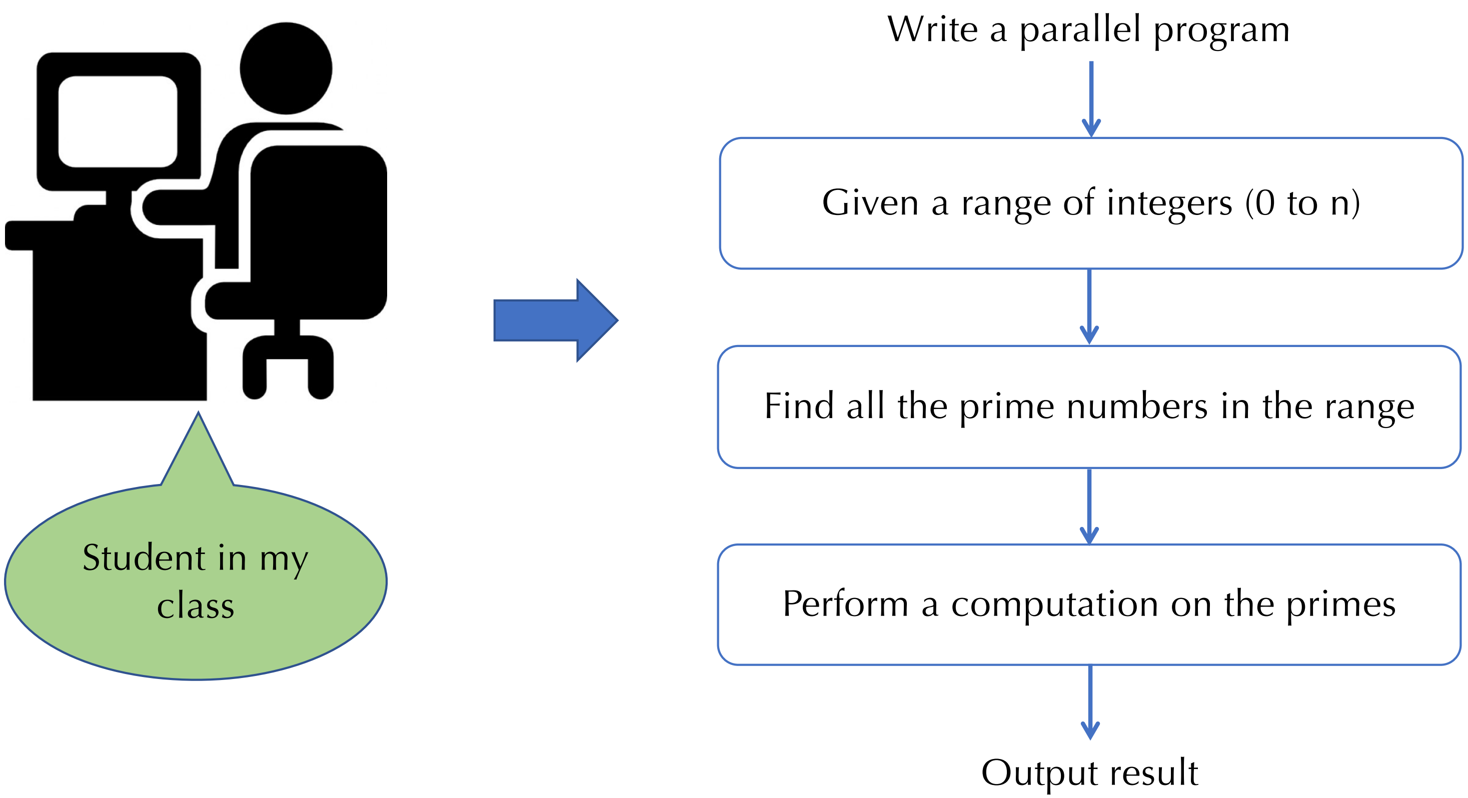
Illustrative Example



Illustrative Example – Writing a Parallel Program

OpenMP™

Feature rich

Work-Sharing | Tasking | SIMD | Offload

Incremental parallelization

```
#pragma omp parallel for
  for(int i=0; i<n; ++i) compute(i);
```

Illustrative Example

Student in my class

1	2	3	4	……..	n

Identify the number of processors on the machine (4)

Divide the range into 4 parts and perform computation

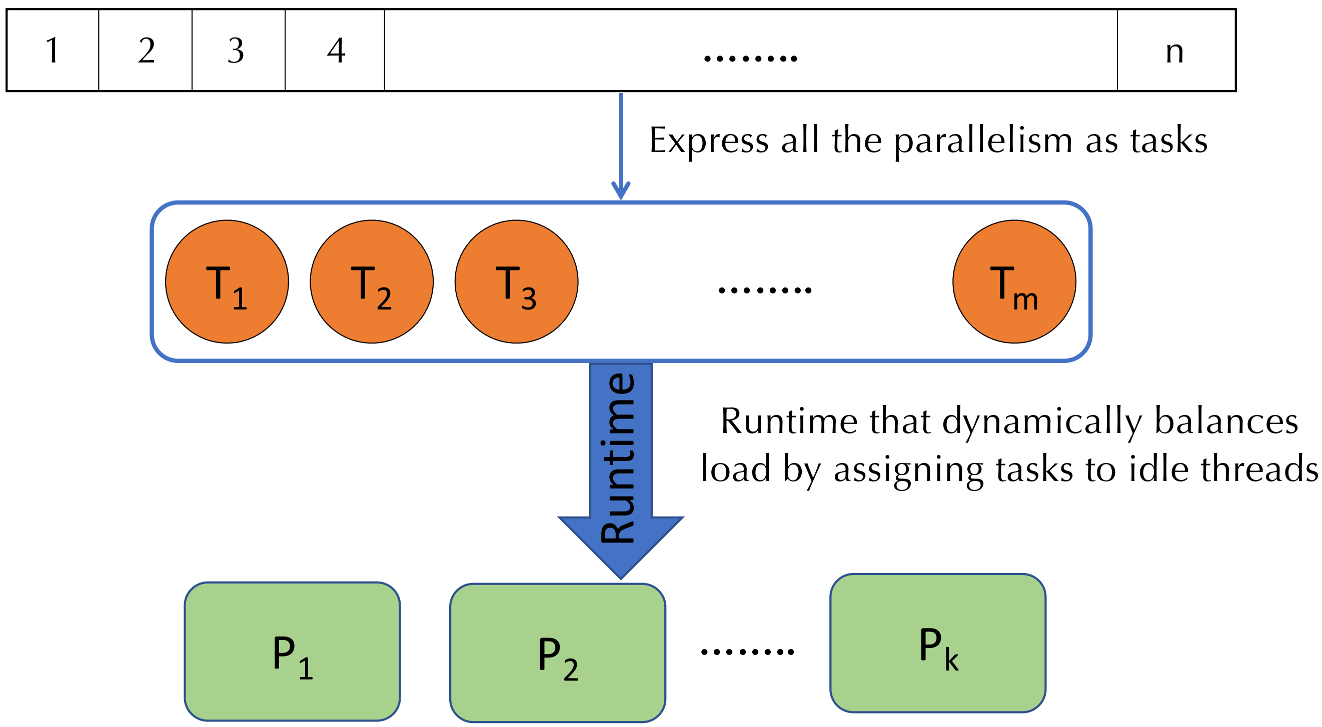
Run: ./primes

Speedup: 1.8X over serial execution

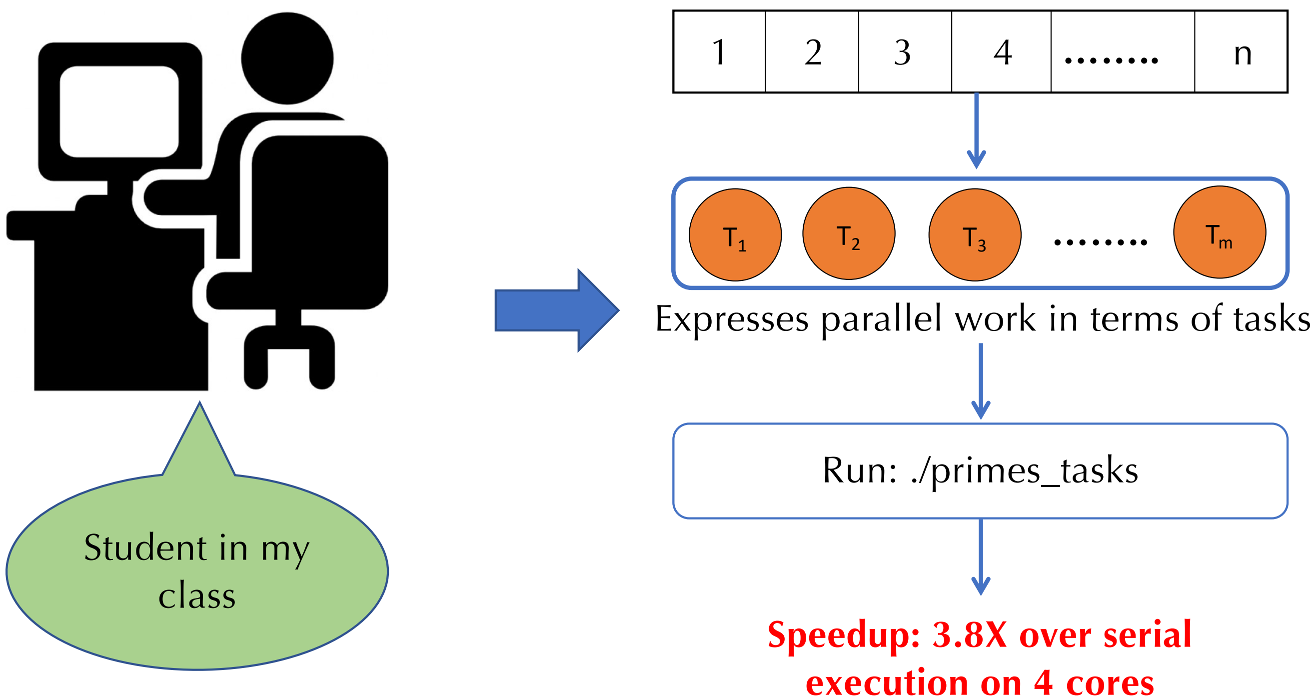
Why?

Load Imbalance

Need to write Performance Portable Code - Advocacy for Task Parallelism



Illustrative Example



Is it performance portable?

Performance Debugging Tools

Coz GProf OProfile ARMMap

arm DDT

PARALLEL STUDIO XE

PARALLELWARE TRAINER

Score-P

scalasca

VAMPIR

- Most of them provide info on frequently executed regions.
- Critical path information is useful
- Coz [SOSP 2015]: Identifies if a line of code matters in increasing speedup on a given machine.

Advisor

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Our Parallelism Profilers and Advisers: TaskProf & OMP-WHIP [FSE 2017, SC 2018, PLDI 2019]

- Making a case for measuring logical parallelism

Series-parallel relations + fine-grained measurements is a performance model

- Where should programmer focus?

Regions with low parallelism => serialization. Critical path!

Profiler

- Does it matter?

Automatically identify regions to increase parallelism to a threshold

What-if Analyses - mimic the effect of parallelization

Adviser

Differential analyses to identify regions with secondary effects

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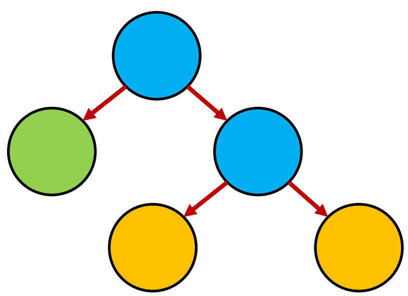
General for multiple parallelism models. This talk focuses on OpenMP

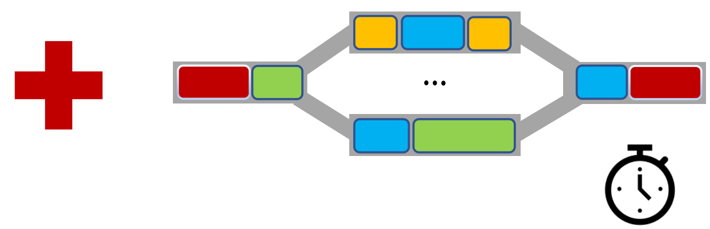
Performance Model for Logical Parallelism and What-If Analyses

Performance Model for Computing Parallelism

- Profile on a machine with low core count and identify scalability bottlenecks
- OSPG: Logical series-parallel relations between parts of a OpenMP program
  - Inspired by prior work: DPST [PLDI 2012], SP Parse tree [SPAA 2015]



OSPG



Fine-grained measurements

OpenMP Series Parallel Graph (OSPG)

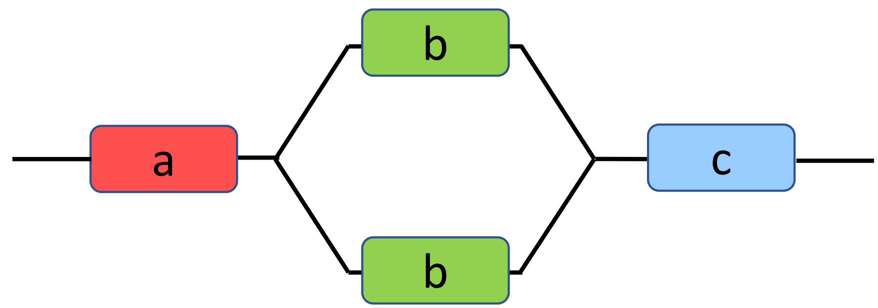
- A data structure to capture series-parallel relations
  - Inspired by Dynamic Program Structure Tree [PLDI 2012]
  - OSPG is an ordered tree in the absence of task dependencies in OpenMP
- Handles the combination of work-sharing (fork-join programs with threads) and tasking
- Precisely captures the semantics of OpenMP
  - Three kinds of nodes : W, S, and P nodes similar to Async, Finish, and Step nodes in the DPST

Code Fragments in OpenMP Programs

OpenMP code snippet

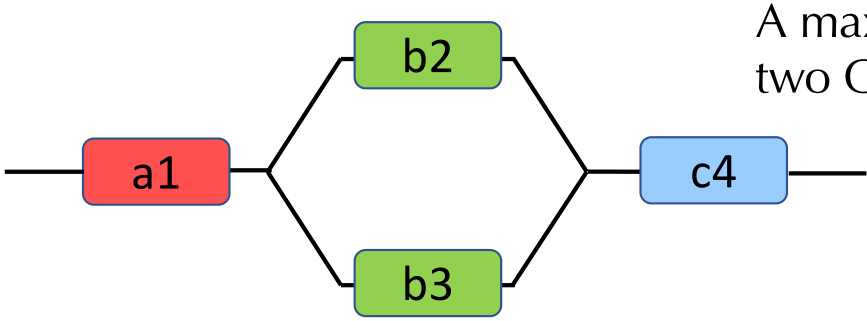
```
…
a();
#pragma omp parallel
  b();
c();
…
```

Execution structure



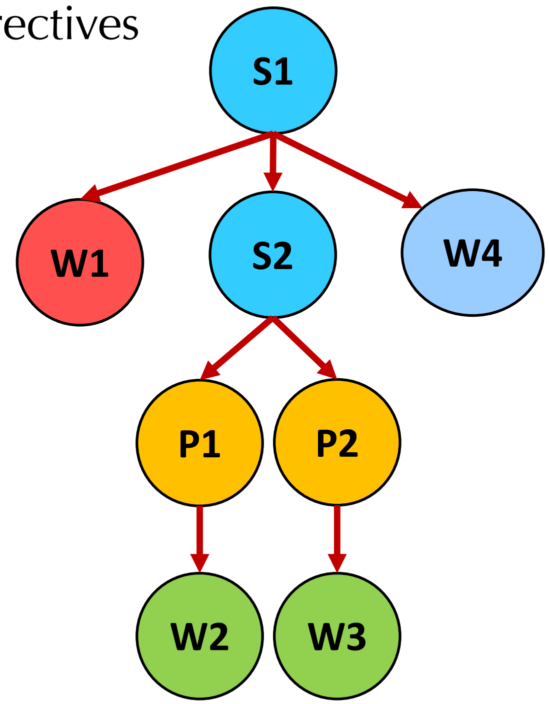
A code fragment is the longest sequence of instructions in the dynamic execution before encountering an OpenMP construct

Capturing Series-Parallel Relation with the OSPG



W-nodes capture computation

A maximal sequence of dynamic instructions between two OpenMP directives



P-nodes capture the parallel relation

Nodes in the sub-tree of a P-node logically executes in **parallel** with right siblings of the P-node

S-nodes capture the series relation

Nodes in the sub-tree of a S-node logically executes in **series** with right siblings of the S-node

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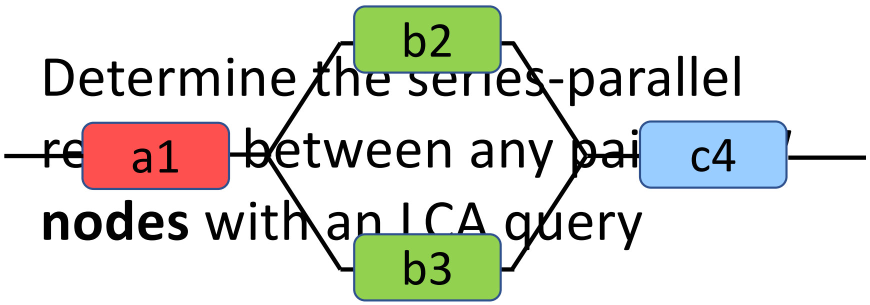
Capturing Series-Parallel Relation with the OSPG

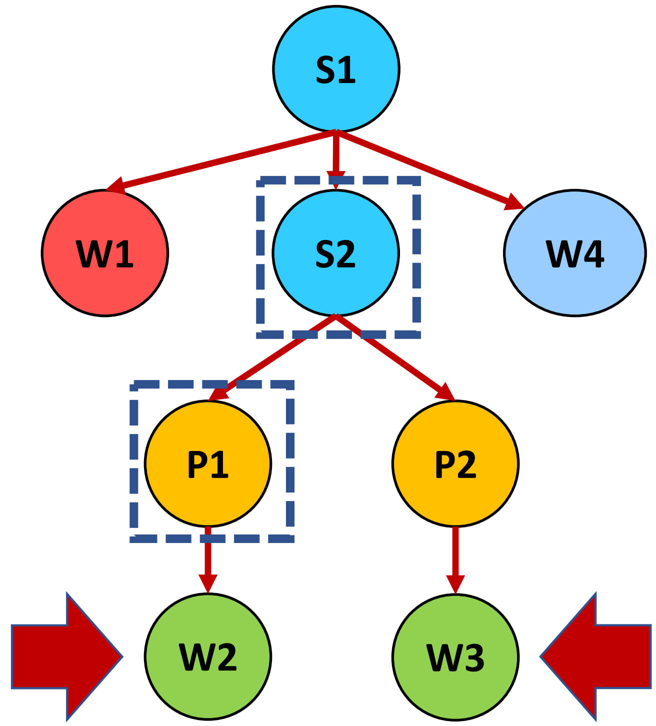
Determine the series-parallel re between any pai **nodes** with an LCA query



Check the type of the LCA's child on the path to the left w-node. If it's a **p-node**, they execute in **parallel**. Otherwise, they execute in **series**

S2 = LCA(W2,W3)

P1 = Left-Child(S2,W2,W3)



Capturing Series-Parallel Relation with the OSPG

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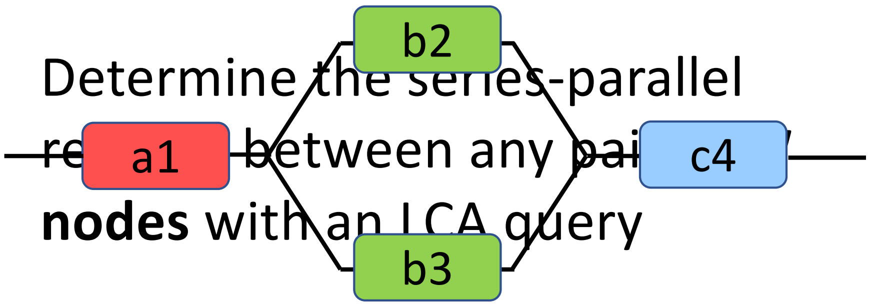
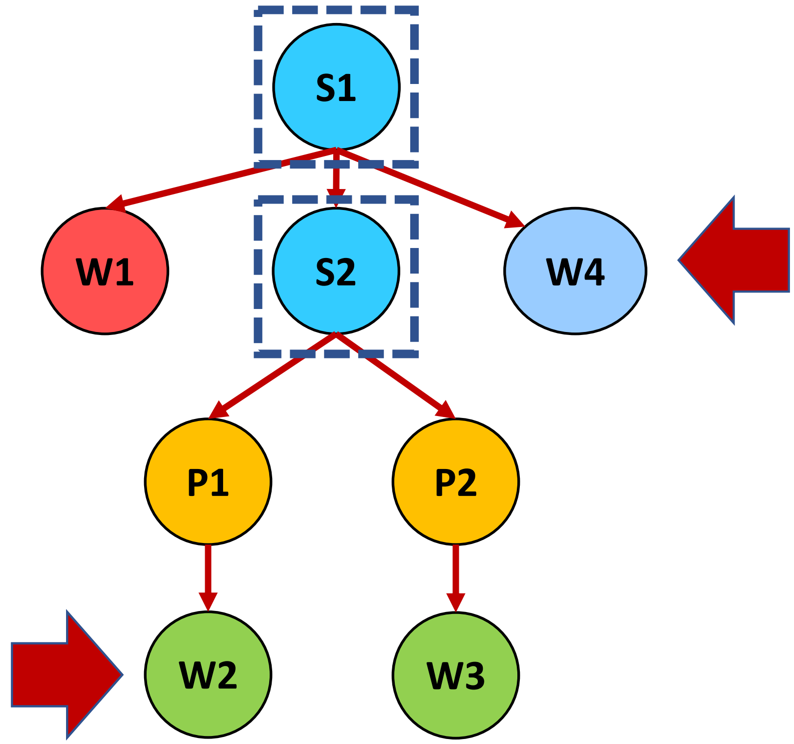


Check the type of the LCA's child on the path to the left w-node. If it's a **p-node**, they execute in **parallel**. Otherwise, they execute in **series**

S1 = LCA(W2,W4)

S2 = Left-Child(S1,W2,W4)



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Profiling an OpenMP Merge Sort Program

- Merge sort program parallelized with OpenMP

```
void main(){
  int* arr = init(&n);
#pragma omp parallel
  #pragma omp single
    mergeSort(arr, 0, n);
}
```

```
void mergeSort(int* arr, int s, int e){
  if (n <= CUT_OFF)
     serialSort(arr, s, e);
  int mid = s + (e-s)/2;
  #pragma omp task
     mergeSort(arr, s, mid);
  #pragma omp task
     mergeSort(arr, mid+1, e);
  #pragma omp taskwait
  merge(arr, s, e);
}
```

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OSPG Construction

```
void main(){
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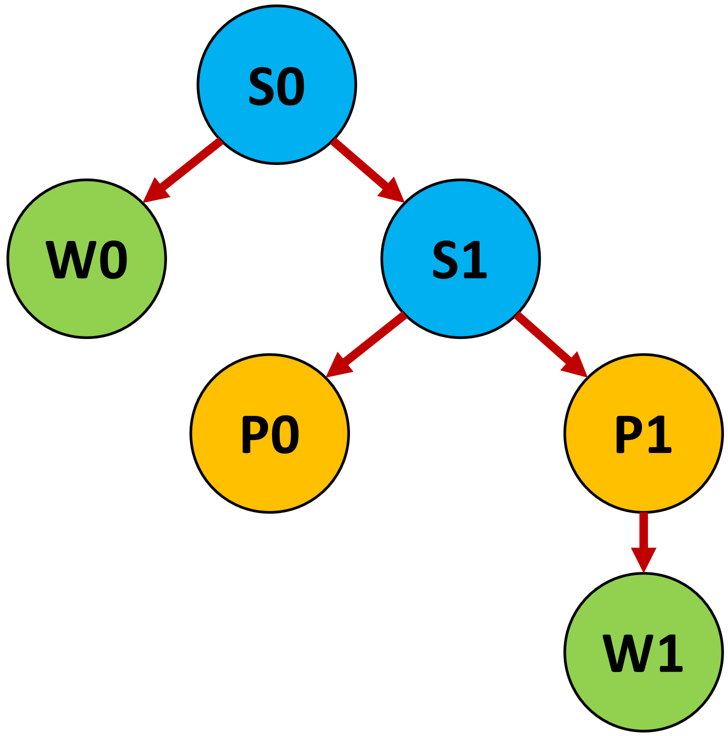

OSPG Construction

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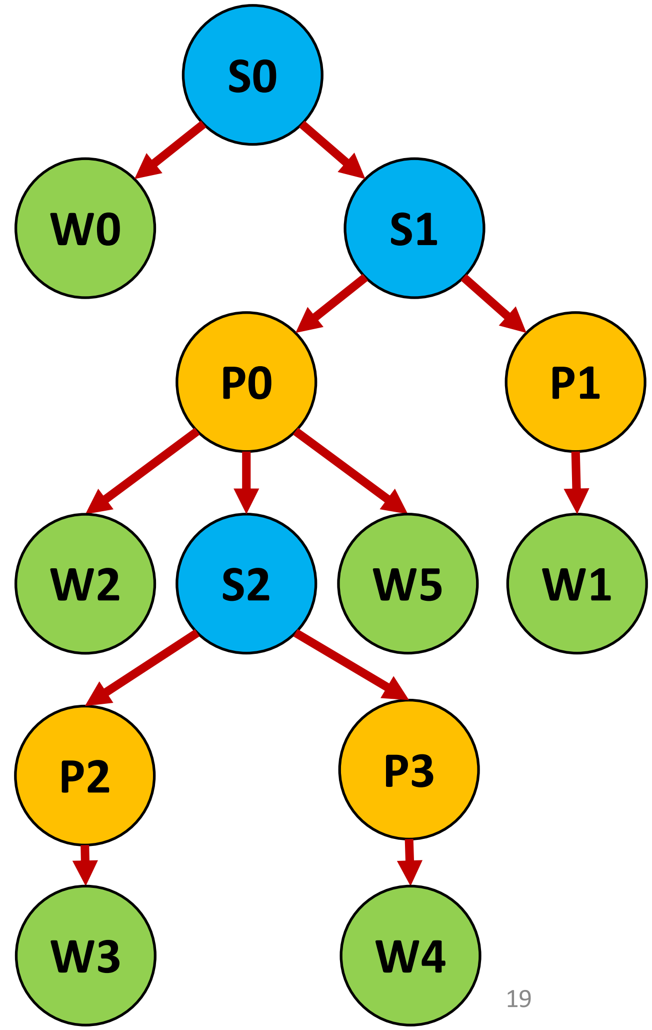

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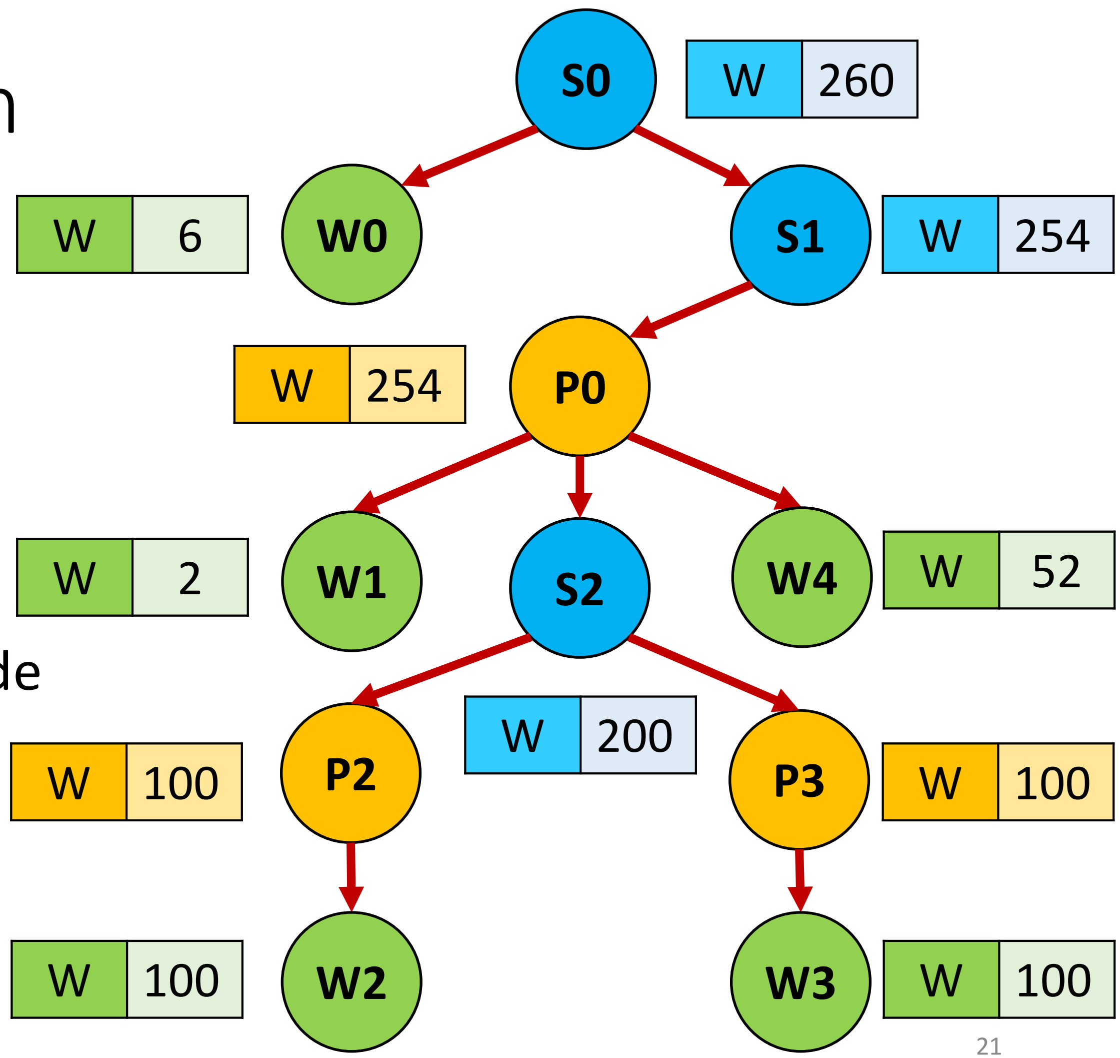
Parallelism Computation Using OSPG

Compute Parallelism

Measure work in each Work node with fine grained measurements

Compute work for each internal node



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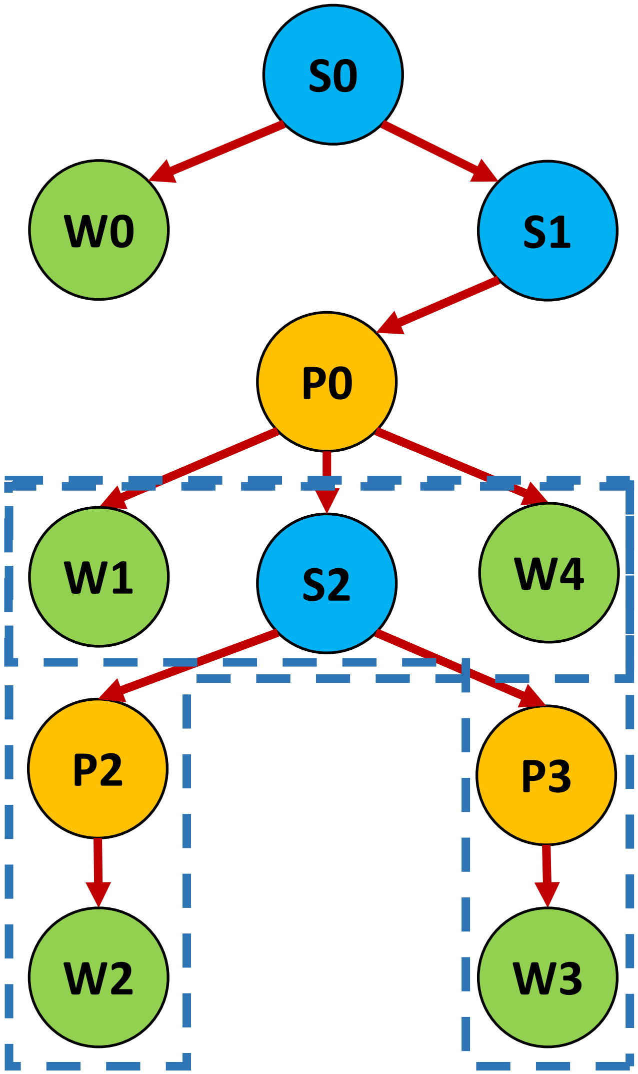
Compute Serial Work

Measure work in each Work node

Compute work for each internal node

Identify serial work on critical path



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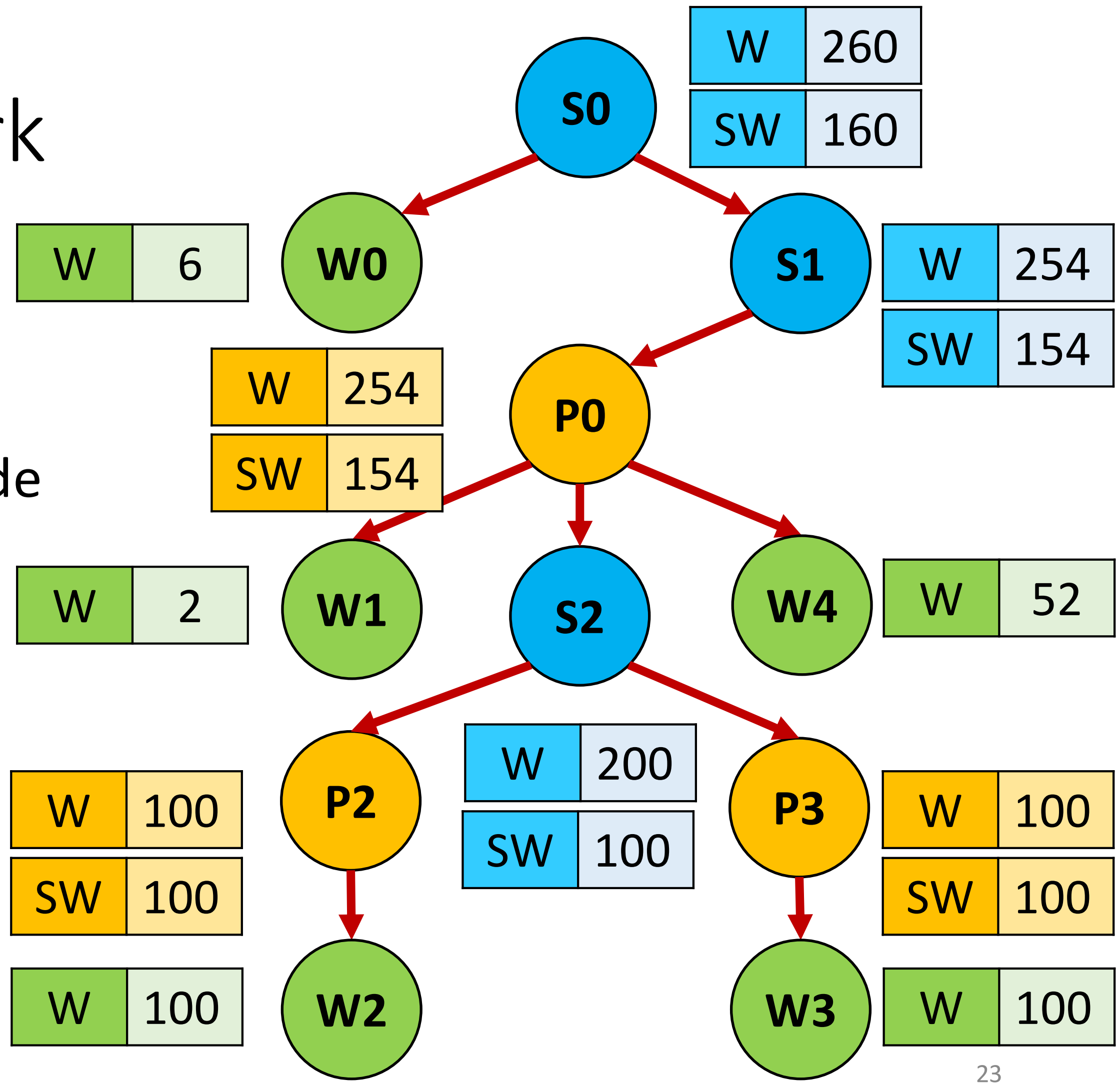
Compute Serial Work

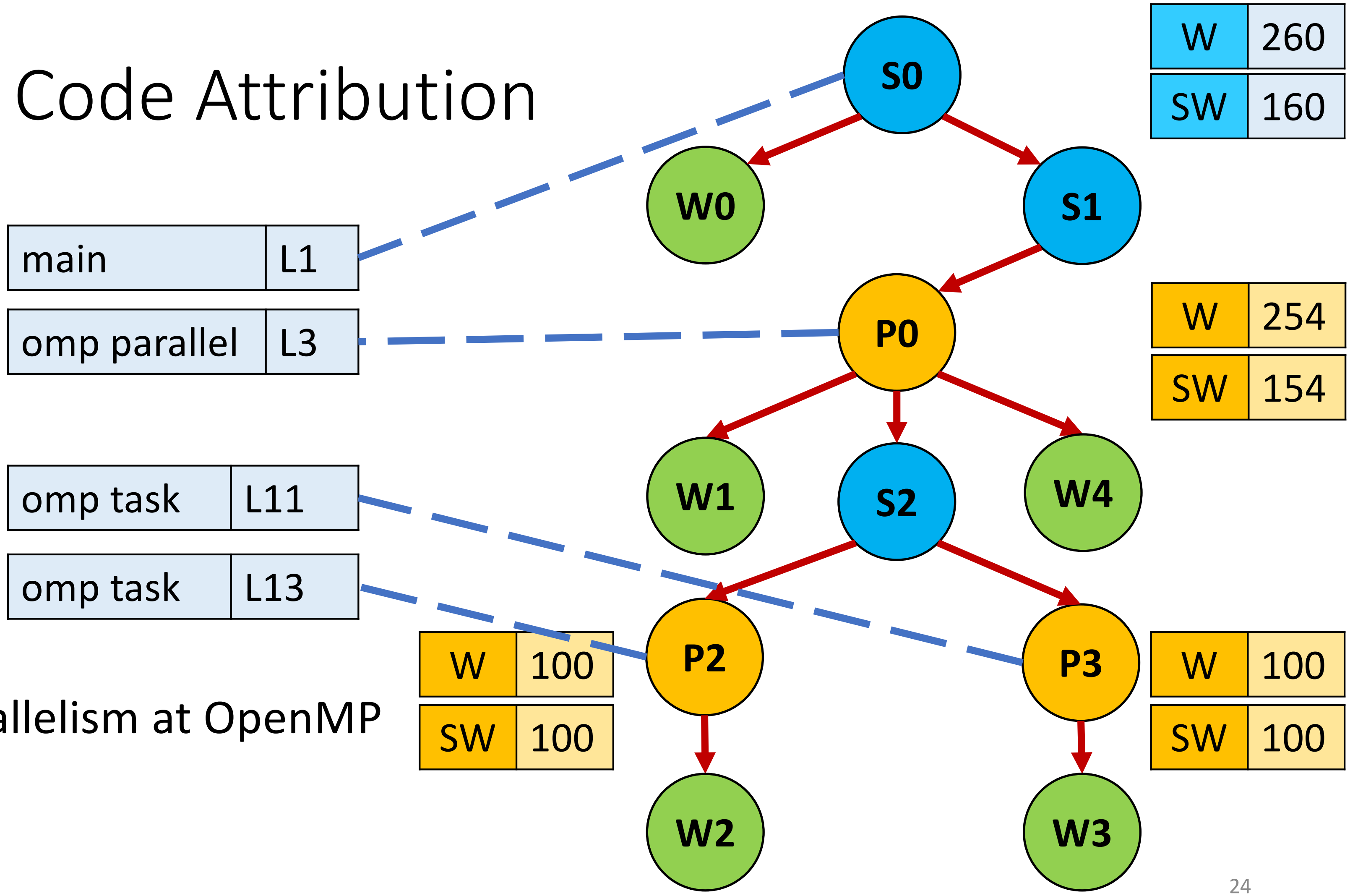
Measure work in each Work node

Compute work for each internal node

Compute serial work for each Internal node



Source Code Attribution



Aggregate parallelism at OpenMP constructs

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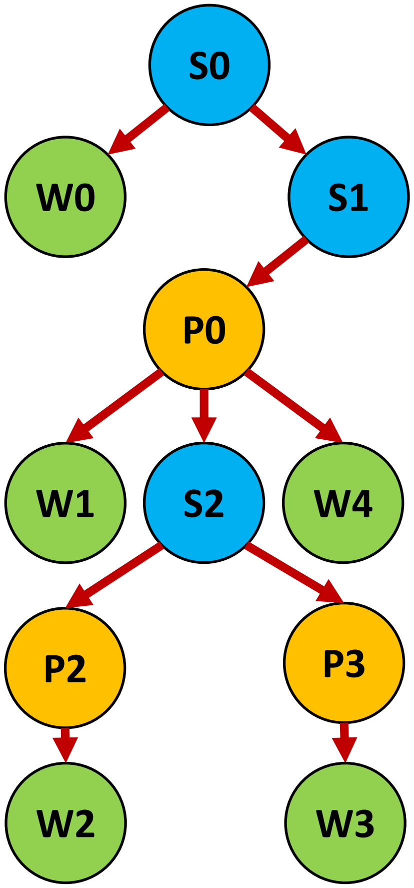
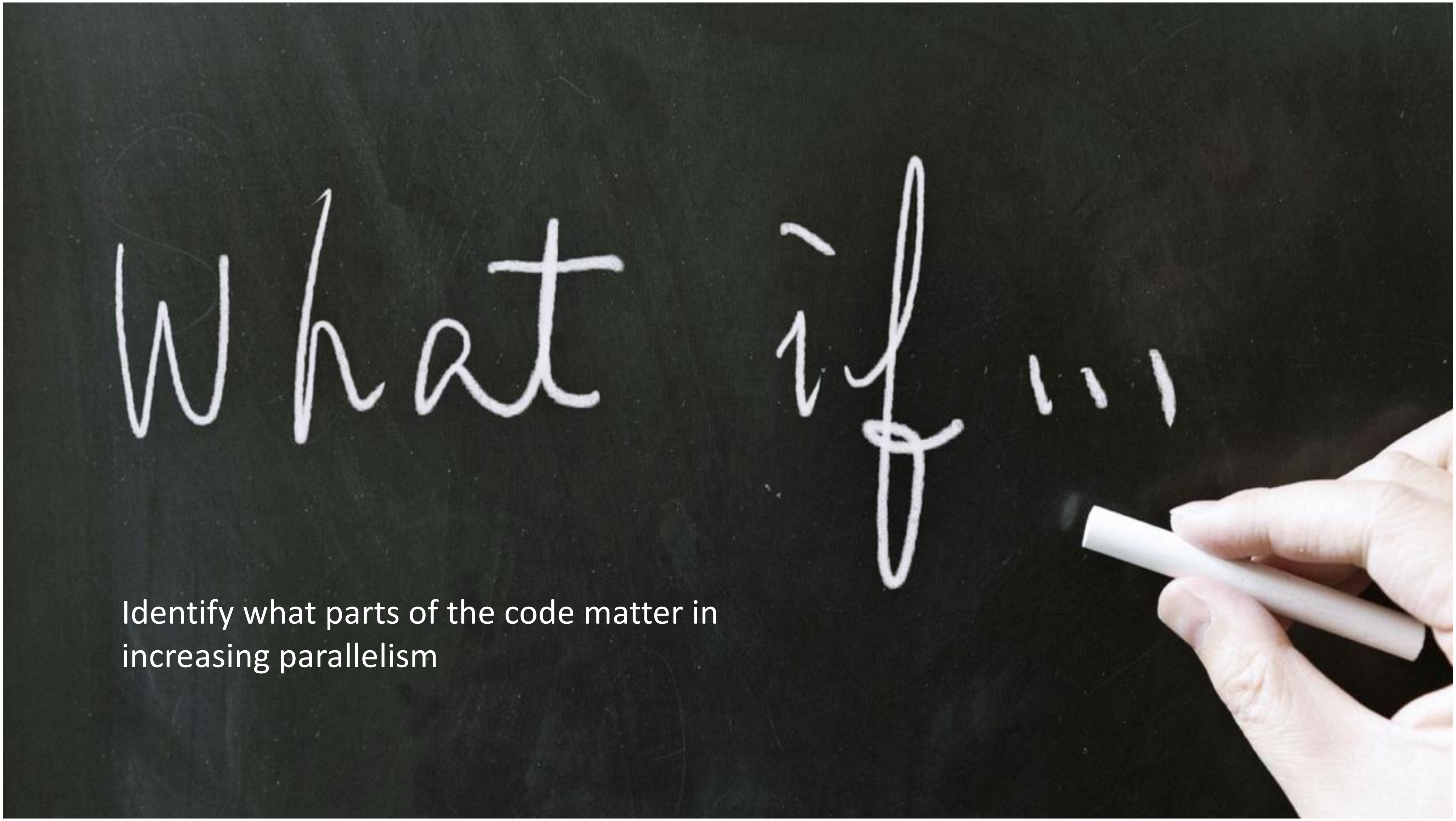
Parallelism Profile

Line Number	Work	Serial Work	Parallelism	Critical Path Work %
program:1	260	160	1.625	3.75
omp parallel:3	254	154	1.65	33.75
omp task:11	100	100	1.00	62.5
omp task:13	100	100	1.00	0





Identify what parts of the code matter in increasing parallelism

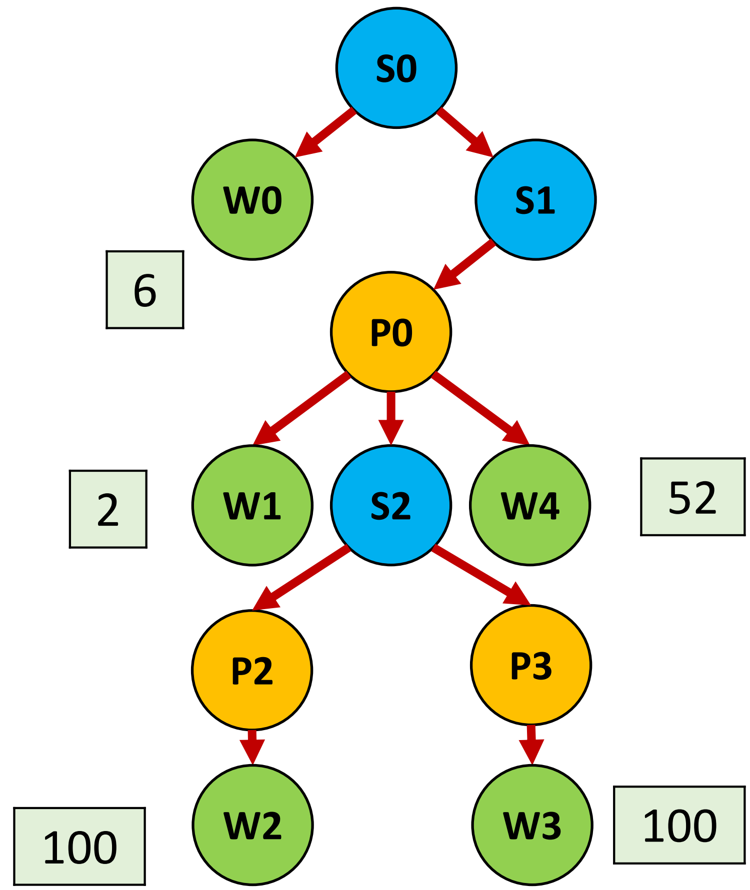
Adviser mode with What-If Analyses

Identify code regions that must be optimized to increase parallelism

Which region to select?

Select a region to optimize

Select step node performing highest work on critical path



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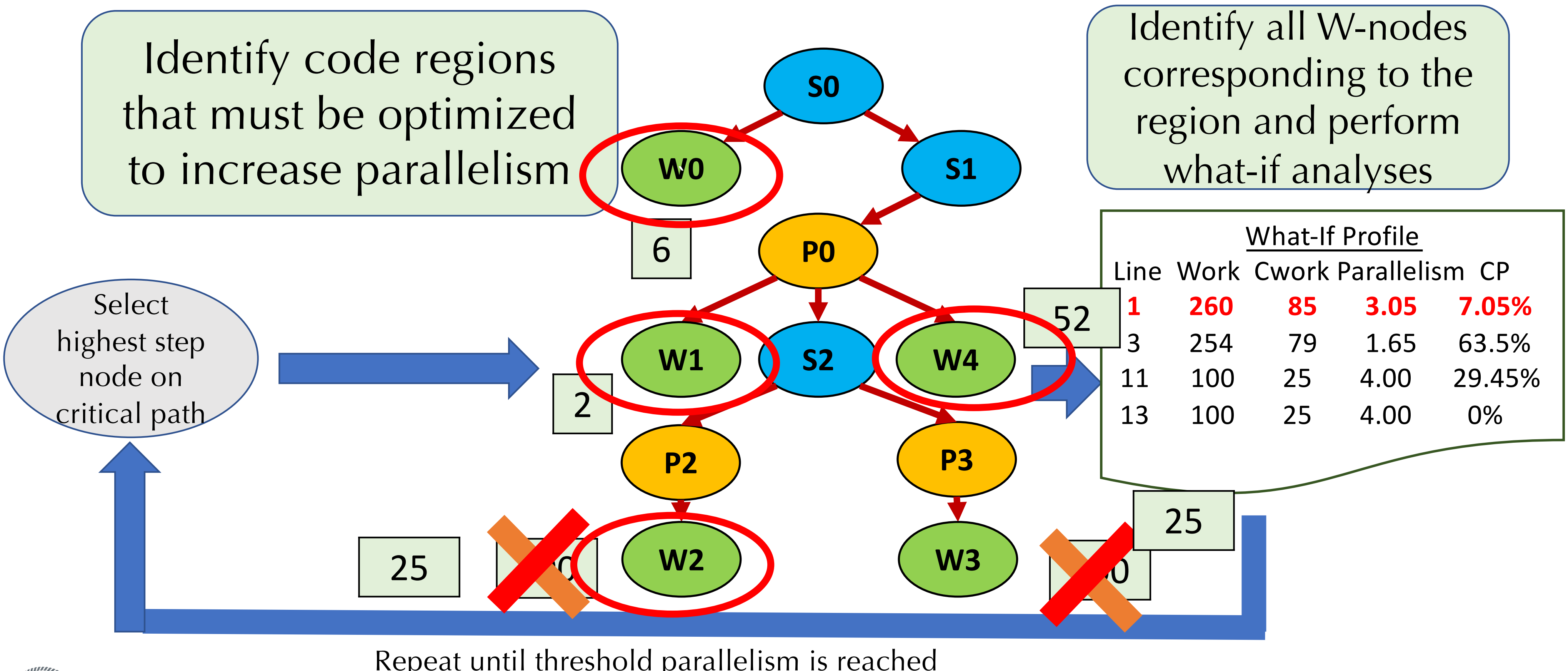
Adviser mode with What-If Analyses



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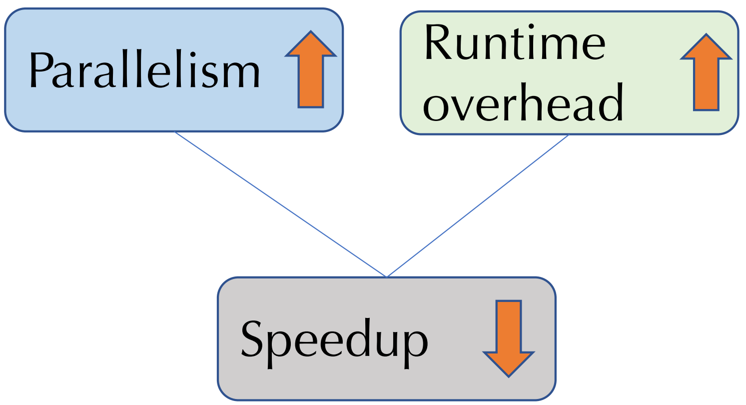
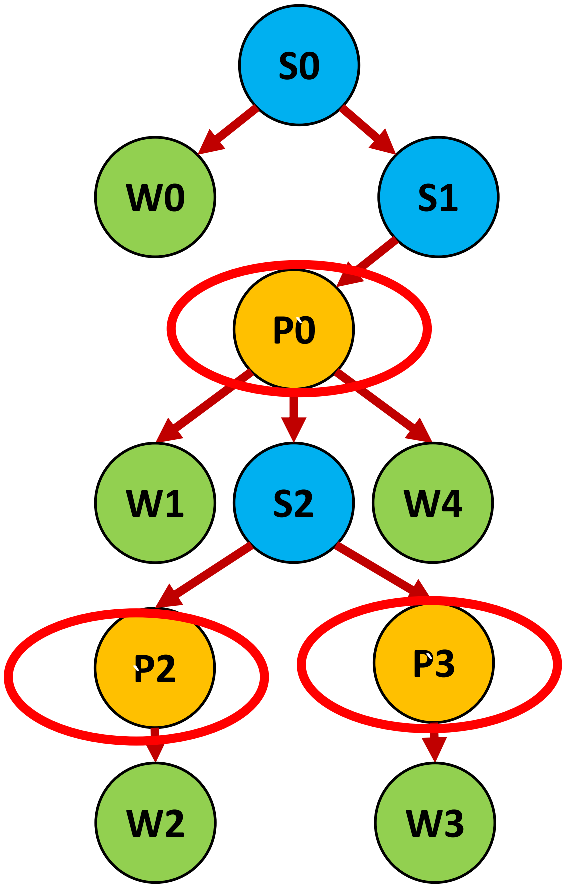
Tasking and Scheduling Overhead





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Adviser mode with What-If Analyses

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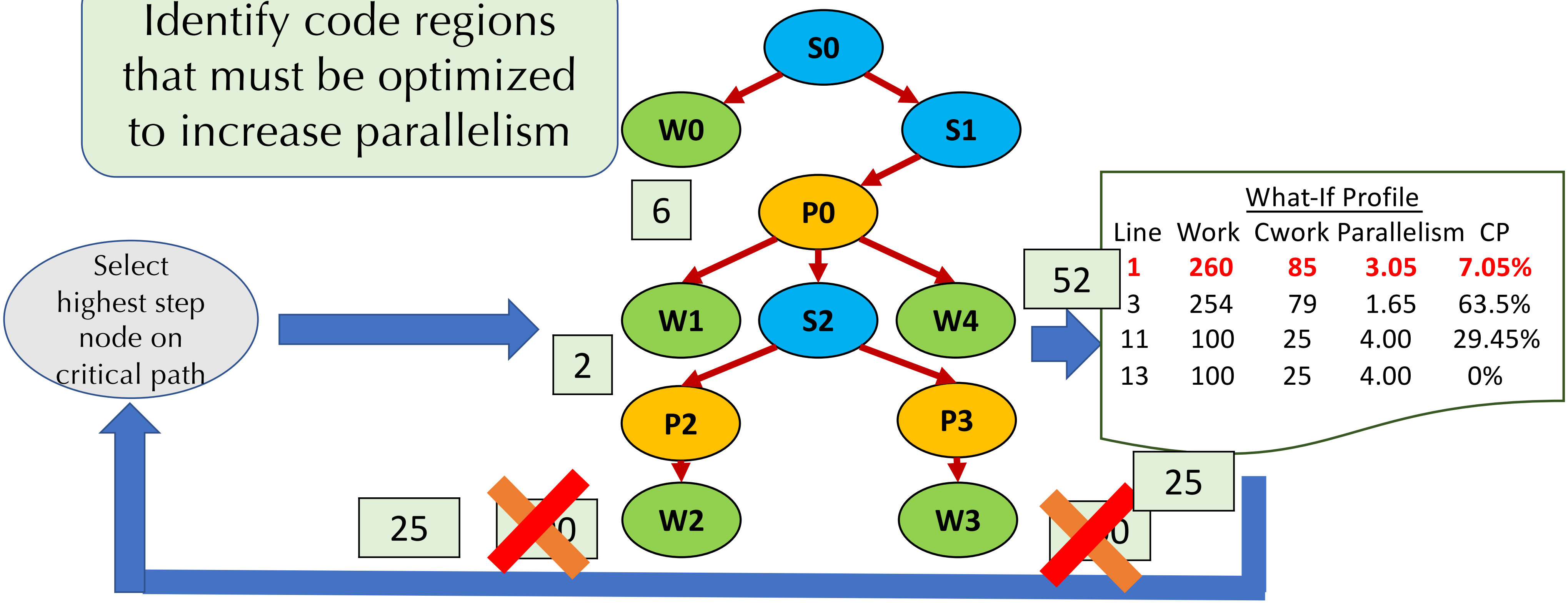

What-If Profile

Line	Work	Cwork	Parallelism	CP
1	**260**	**85**	**3.05**	**7.05%**
3	254	79	1.65	63.5%
11	100	25	4.00	29.45%
13	100	25	4.00	0%

Repeat until threshold parallelism is reached

OR

Work of highest step node < K * average tasking overhead

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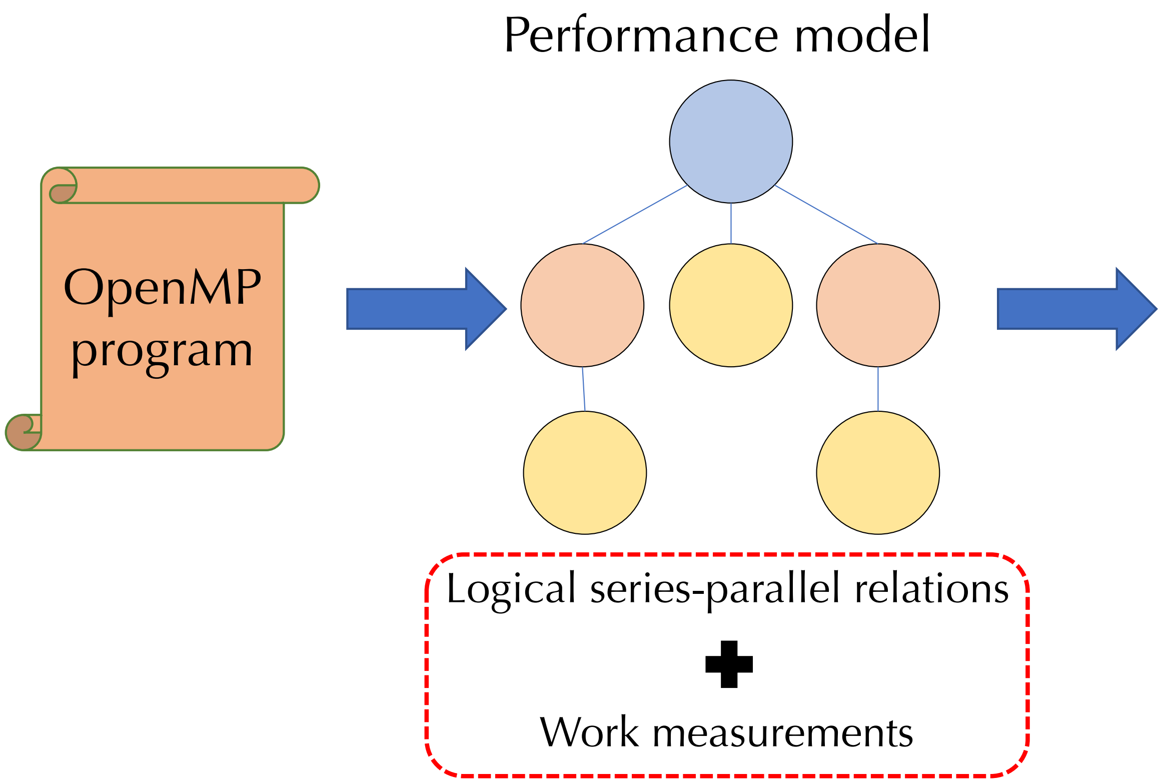
Recap



Parallelism Profile

Line	Work	Cwork	Parallelism
12	160	130	1.23
….	….	….	…..

What-if Regions

Region	Parallelization
12 - 14	4X
…. ….	…. …..

What-if Profile

Line	Work	Cwork	Parallelism
12	160	130	16.12
….	….	….	…..

Differential Analysis to Identify Secondary Effects

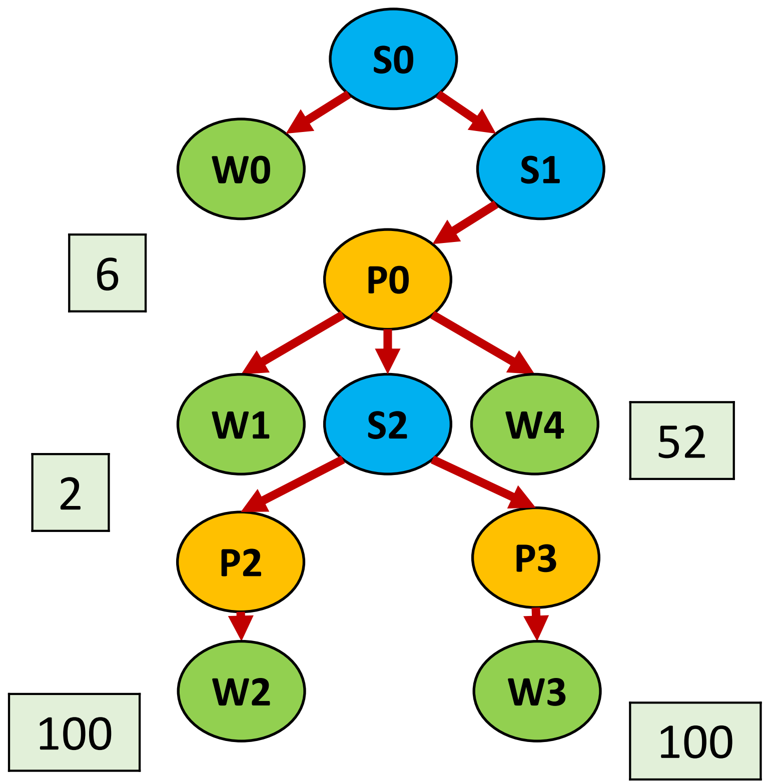
Beyond Parallelism - Secondary Effects

- Program can have high parallelism, but low speedup
  - Secondary effects of parallel execution on hardware

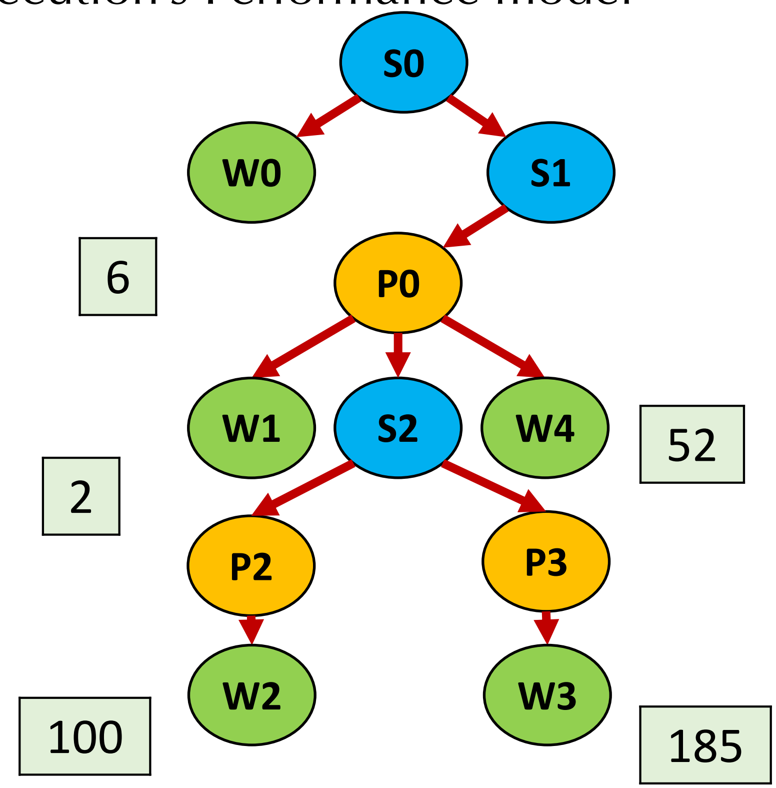
- Contention for a system resource
  - Cache – False sharing
  - Memory – High remote memory accesses
  - LLC misses - Reduced locality
  - Processor to data affinity

Differential Analysis

Oracle Performance model



Parallel Execution's Performance model



Work inflation in region with secondary effects

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Inflation over Multiple Metrics

Differential Counters

Cycles
HITM
Remote DRAM
accesses
……

Differential Profile

Regions	Cycles	HITM	RemDRAM
main	**4.19X**	**13.2X**	**1.1X**
2-4	**5.34X**	**17.8X**	1X
14-15	1.02X	1.03X	1X
15-16	1.03X	1.1X	1.01X

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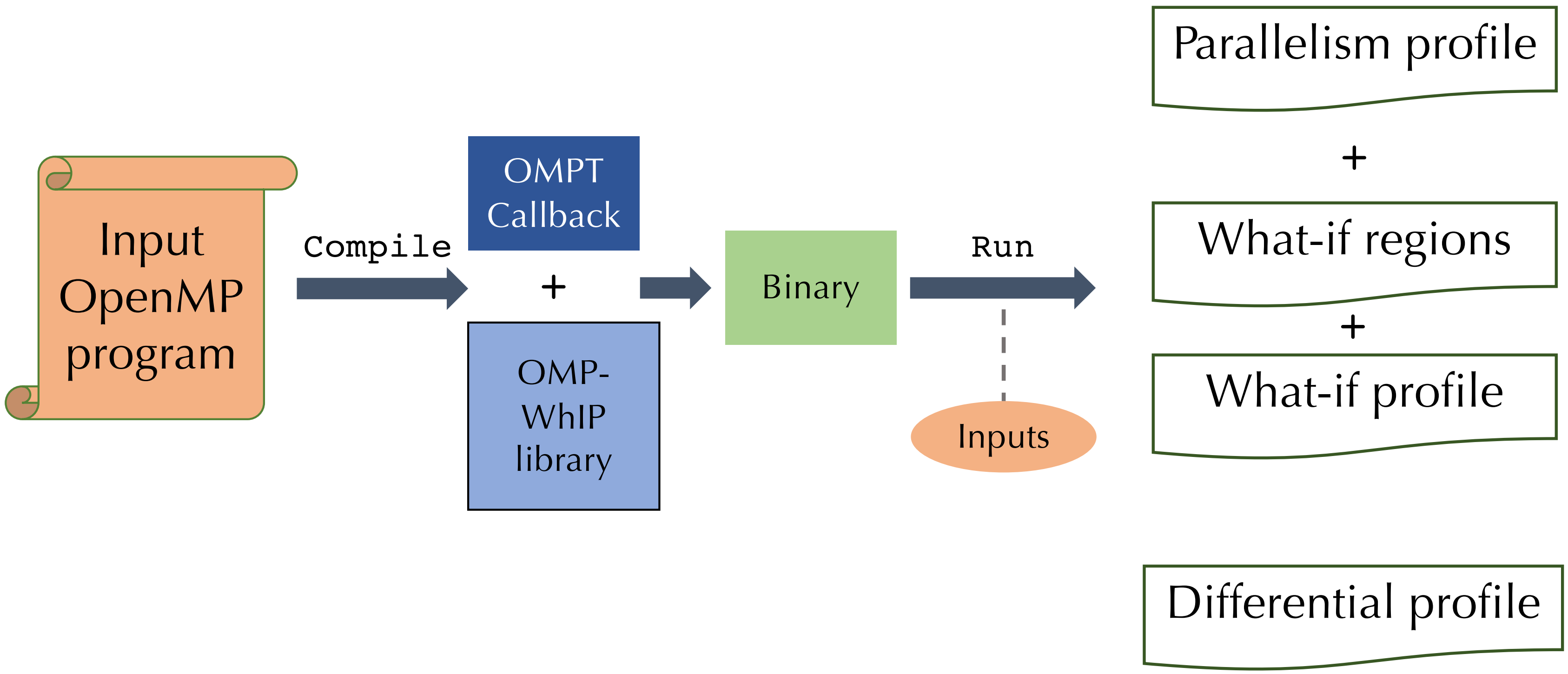
Prototypes for OpenMP and Task Parallelism

OMP-WHIP for OpenMP programs: https://github.com/rutgers-apl/omp-whip/
TaskProf for Intel TBB programs: https://github.com/rutgers-apl/TaskProf2



Optimizing MILCmk

Initial Parallelism Profile

Parallelism Profile

File:Line	Parallelism	Cpath
main	**44.21**	**28.3**
vmeq.c:23	30.29	23.3
veq.c:28	32.83	19.55
vpeq.c:28	33.55	9.35
….	….	…..

What-if Profile

What-if Regions
funcs.c:81 – 91
funcs.c:60 – 67
funcs.c:47 - 54

What-if Profile

File:Line	Parallelism	Cpath
main	**89.89**	**21.3**
vmeq.c:23	30.29	25.2
veq.c:28	32.83	21.5
vpeq.c:28	33.55	11.5
….	….	…..

Optimizing MILCmk

```
QLA_Real
sum_V(QLA_ColorVector *d, int n)
{
  QLA_Real t=0, *r=(QLA_Real *)d;
  int nn = n*sizeof(QLA_ColorVector)/sizeof(QLA_Real);
  for(int i=0; i<nn; i++) t += r[i];
  return t/nn;
}
```

Replaced serial for loop with parallel_reduce

```
QLA_Real
sum_H(QLA_HalfFermion *d, int n)
{
  QLA_Real t=0, *r=(QLA_Real *)d;
  int nn = n*sizeof(QLA_HalfFermion)/sizeof(QLA_Real);
  for(int i=0; i<nn; i++) t += r[i];
  return t/nn;
}
```

```
QLA_Real
sum_D(QLA_DiracFermion *d, int n)
{
  QLA_Real t=0, *r=(QLA_Real *)d;
  int nn = n*sizeof(QLA_DiracFermion)/sizeof(QLA_Real);
  for(int i=0; i<nn; i++) t += r[i];
  return t/nn;
}
```

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Optimizing MILCmk

Initial Differential Profile

	Differential Profile		
File:Line	Cycles	rem HITM	rem DRAM
main	**3.0X**	**100.4X**	**84.8X**
veq.c:28-35	3.8X	55X	78X
vmeq.c:20-22	3.7X	102X	61X
vpeq.c:20-27	3.6X	91X	68X
….	….	…..	…..

- Inflation in cycles and remote DRAM accesses in 5 parallel_for regions
- parallel_for loops were repeated multiple times
  - Lack of affinity
- Optimized by replacing default partitioner with affinity partitioner

Increased the speedup of MILCmk from 2.2X to 6X

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Is it Useful?

We found it to be effective with numerous applications.

Currently in talks for tech transfer with the Intel Vtune team.

Open Source at
https://github.com/rutgers-apl/TaskProf2
https://github.com/rutgers-apl/omp-whip/

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Conclusion

- Make a case for measuring logical parallelism
- Series-parallel relations + fine-grained measurements ➔ a useful performance model for identifying scalability bottlenecks
- What-if analyses can help you identify regions that matter
- Differential analyses to identify regions having secondary effects
- Applicable to wide variety of programming models with appropriate series-parallel graphs

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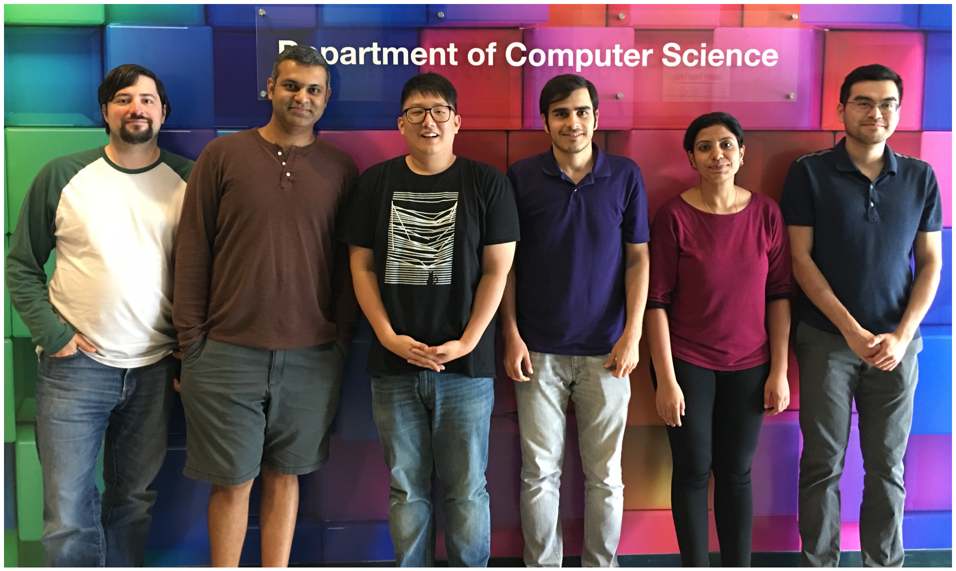
Develop Abstractions for Performance & Correctness



Alive-NJ: https://github.com/rutgers-apl/alive-nj/

TaskProf2: https://github.com/rutgers-apl/TaskProf2

OMP-WHIP: https://github.com/rutgers-apl/omp-whip/

CASM-Verify: https://github.com/rutgers-apl/CASM-Verify/

Other software prototypes from the
Rutgers Architecture & Programming Languages Group:
https://github.com/rutgers-apl/

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