NORTHWEST INSTITUTE for ADVANCED COMPUTING

Pacific Northwest NATIONAL LABORATORY
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UNIVERSITY of WASHINGTON

AMATH 483/583
High Performance Scientific Computing

Lecture 11:
Threads, Shared Memory Parallelism

Andrew Lumsdaine
Northwest Institute for Advanced Computing
Pacific Northwest National Laboratory
University of Washington
Seattle, WA

Announcements

- Mid Term out this evening (2019-05-07) due 11:59PM 2019-05-14
- Guest lecturer 2019-05-09
- “Pop quiz” next week 2019-05-14 or 2019-05-16
  - (Extra credit only)

Overview

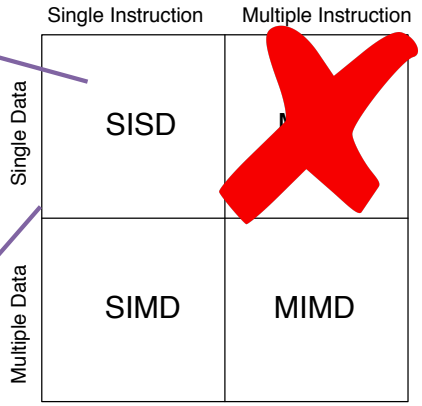
- Multiple cores
- Processes / threads as resource / computation abstraction
- Parallelization strategies for multiple computations
- Correctness
- Performance

Flynn's Taxonomy (Aside)

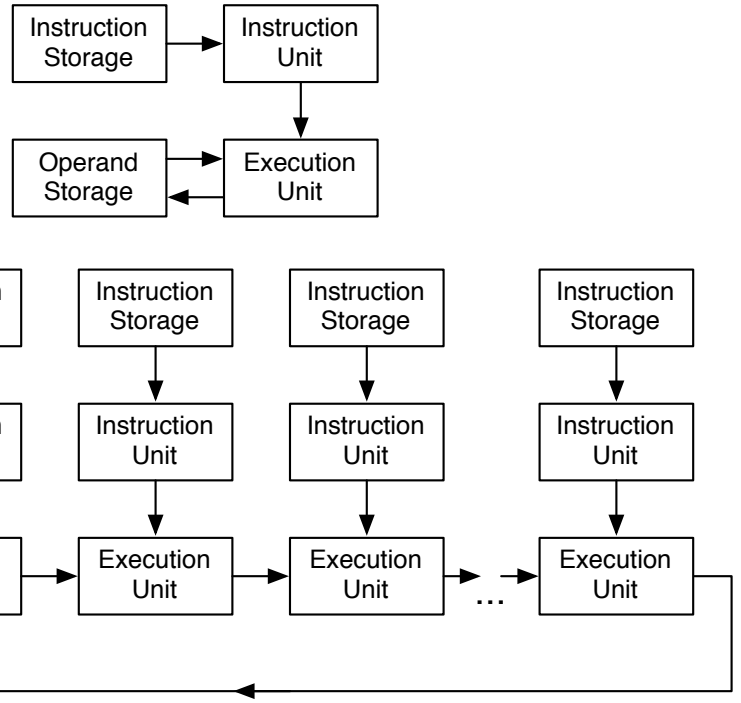
Anyone in HPC must know Flynn's taxonomy

- **Classic** classification of parallel architectures (Michael Flynn, 1966)

Plain old sequential

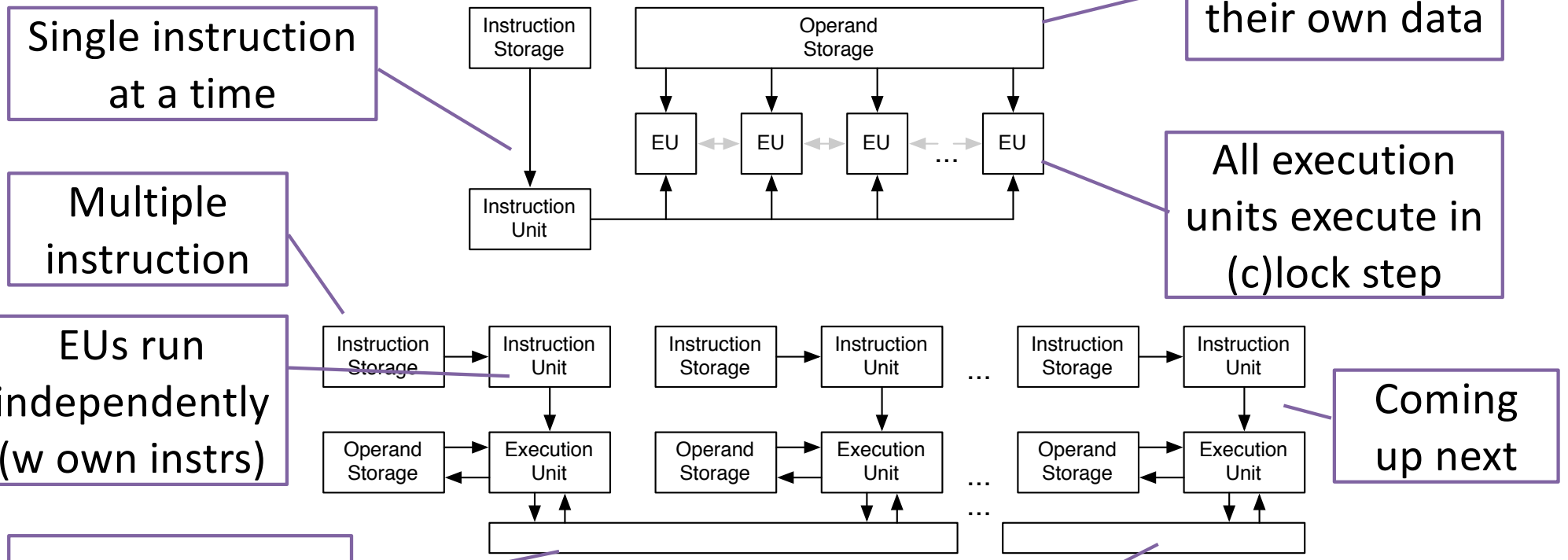


Based on multiplicity of instruction streams, data storage



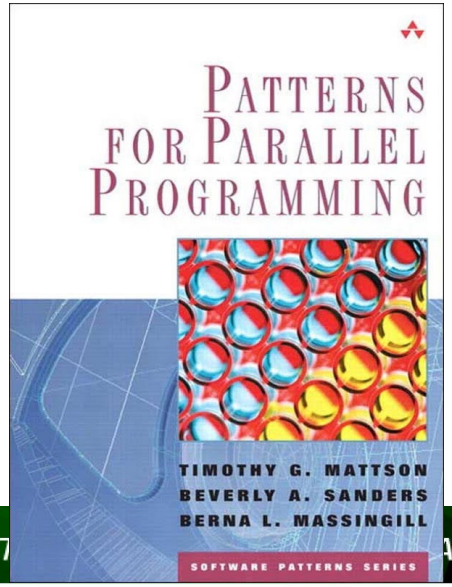
SIMD and MIMD

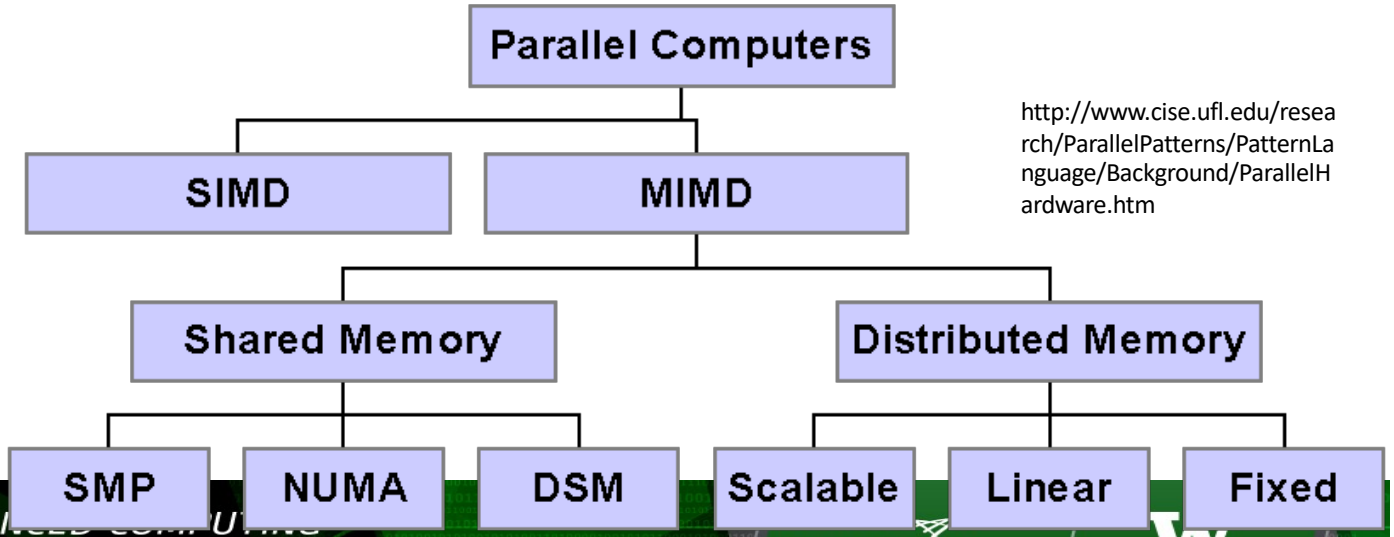
- Two principal parallel computing paradigms (multiple c



A More Refined (Programmer-Oriented) Taxonomy

- Three major modes: SIMD, Shared Memory, Distributed Memory
- Different programming approaches are generally associated with different modes of parallelism (threads for shared, MPI for distributed)
- A modern supercomputer will have all three major modes present





http://www.cise.ufl.edu/research/ParallelPatterns/PatternLanguage/Background/ParallelHardware.htm

Multicore Architecture

Core is a FDREW + regs

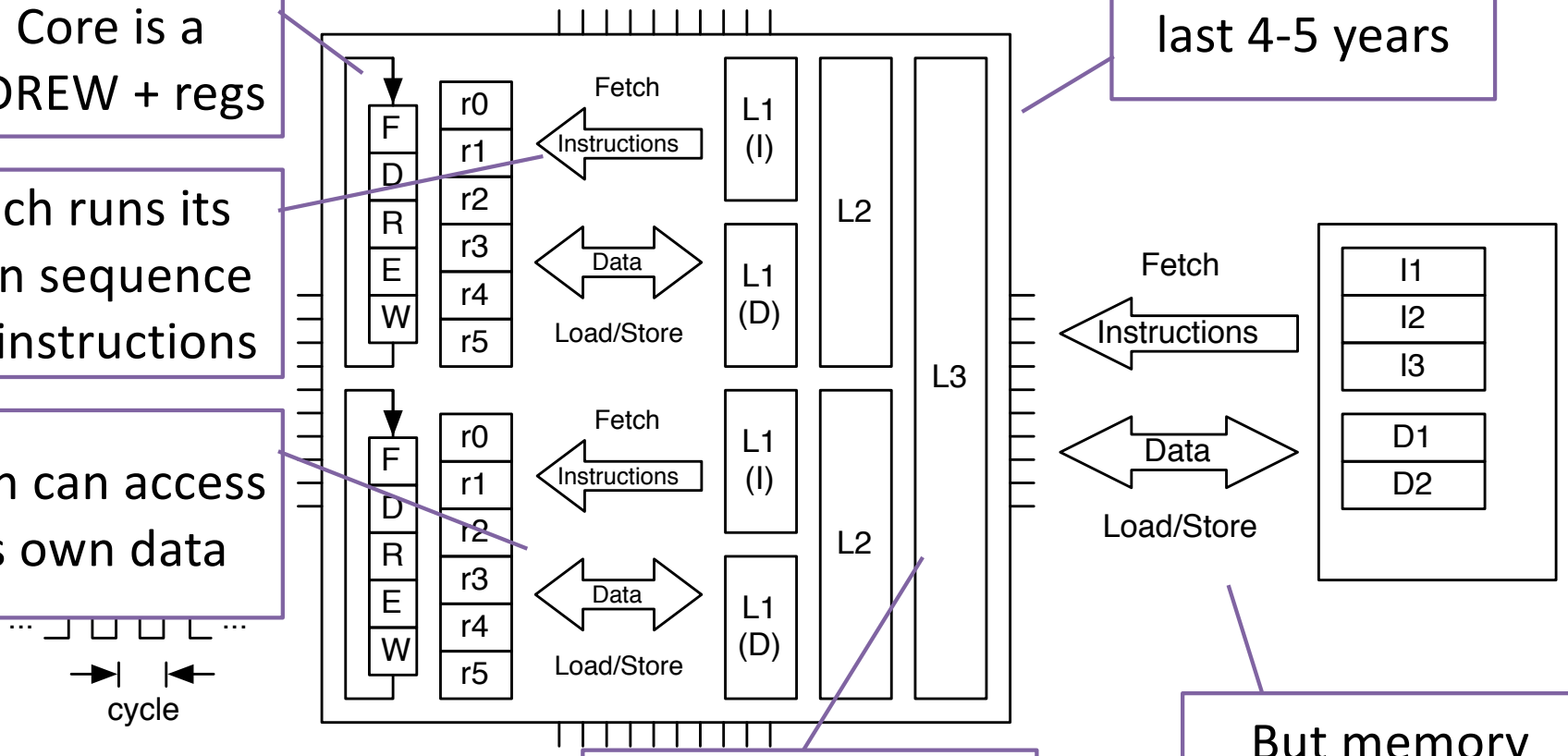
Each runs its own sequence of instructions

Each can access its own data

Any CPU in the last 4-5 years

Each has memory hierarchy

But memory might be shared



Process Abstraction

Stored in Process Control Block (PCB

Set of information about process resources

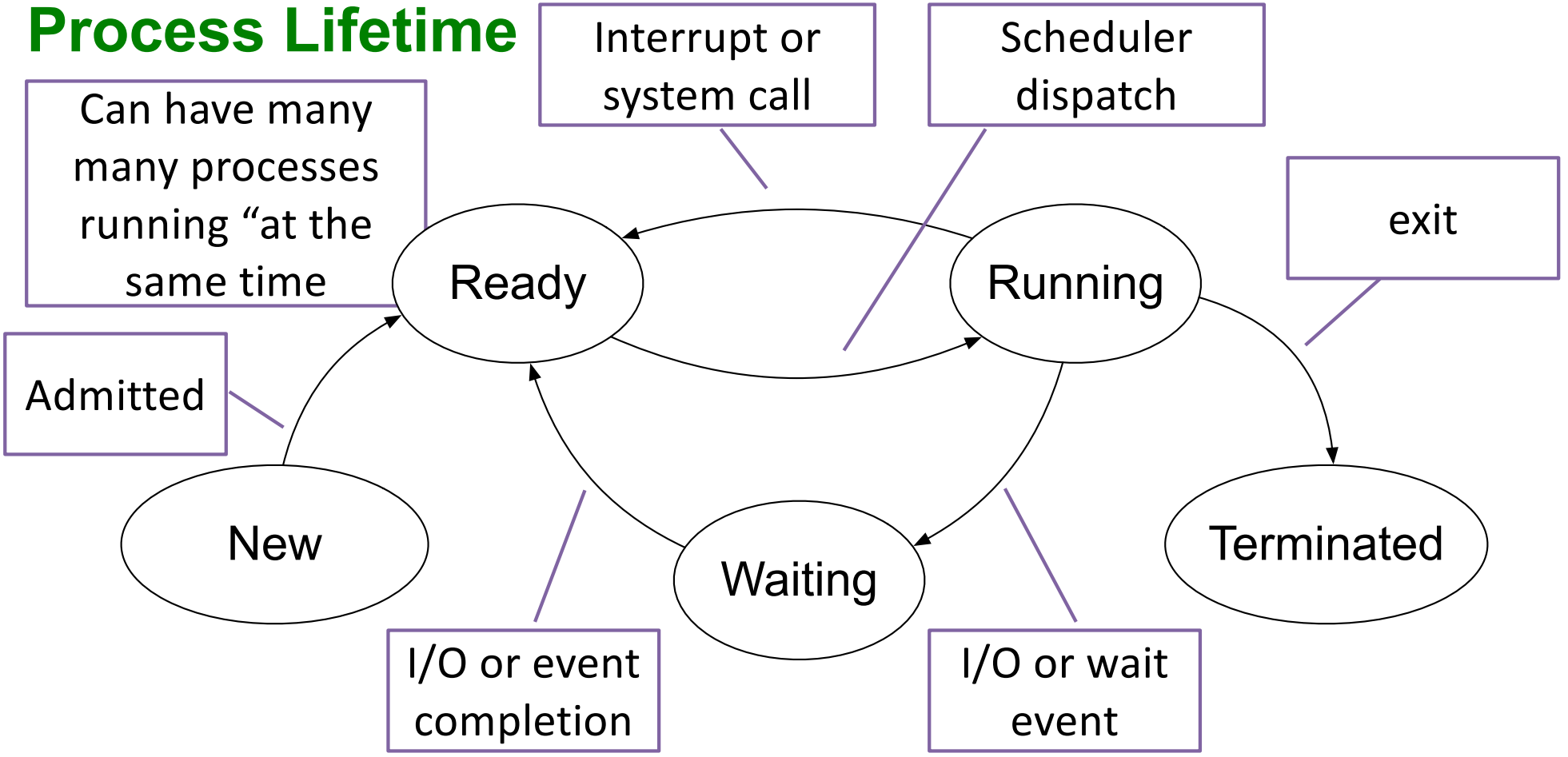
Sufficient to be able to start a process after stopped

Also for accounting / administrative purposes

Process management	**Memory management**	**File management**
Registers	Pointer to text segment	Root directory
Program counter	Pointer to data segment	Working directory
Program status word	Pointer to stack segment	File descriptors
Stack pointer		User ID
Process state		Group ID
Priority		
Scheduling parameters		
Process ID		
Parent process		
Process group		
Signals		
Time when process started		
CPU time used		
Children's CPU time		
Time of next alarm		

What does program counter represent?

Process Lifetime



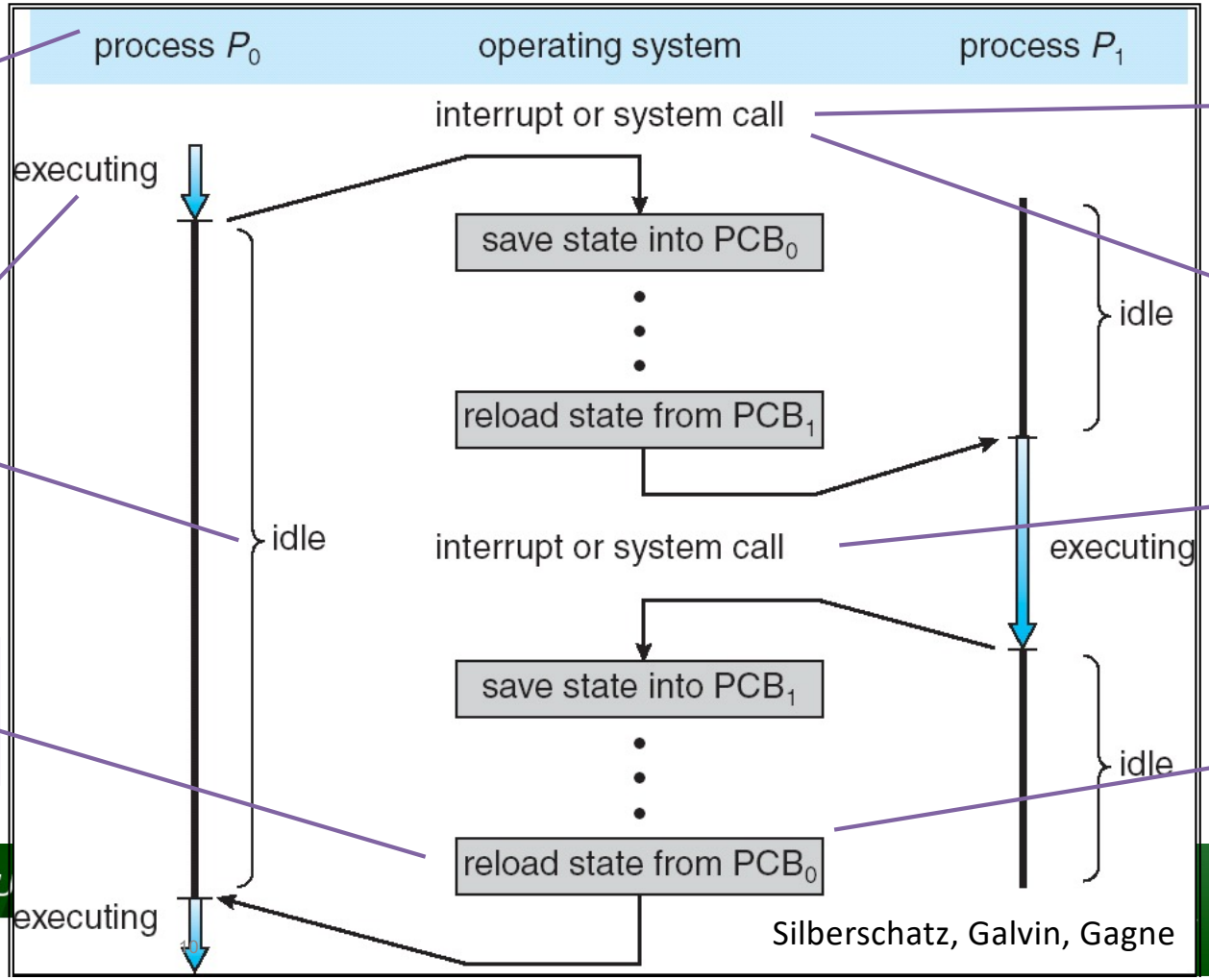
Context Switch

P0 and P1 are running processes

What does this mean?

And this?

PCB = Process Control Block



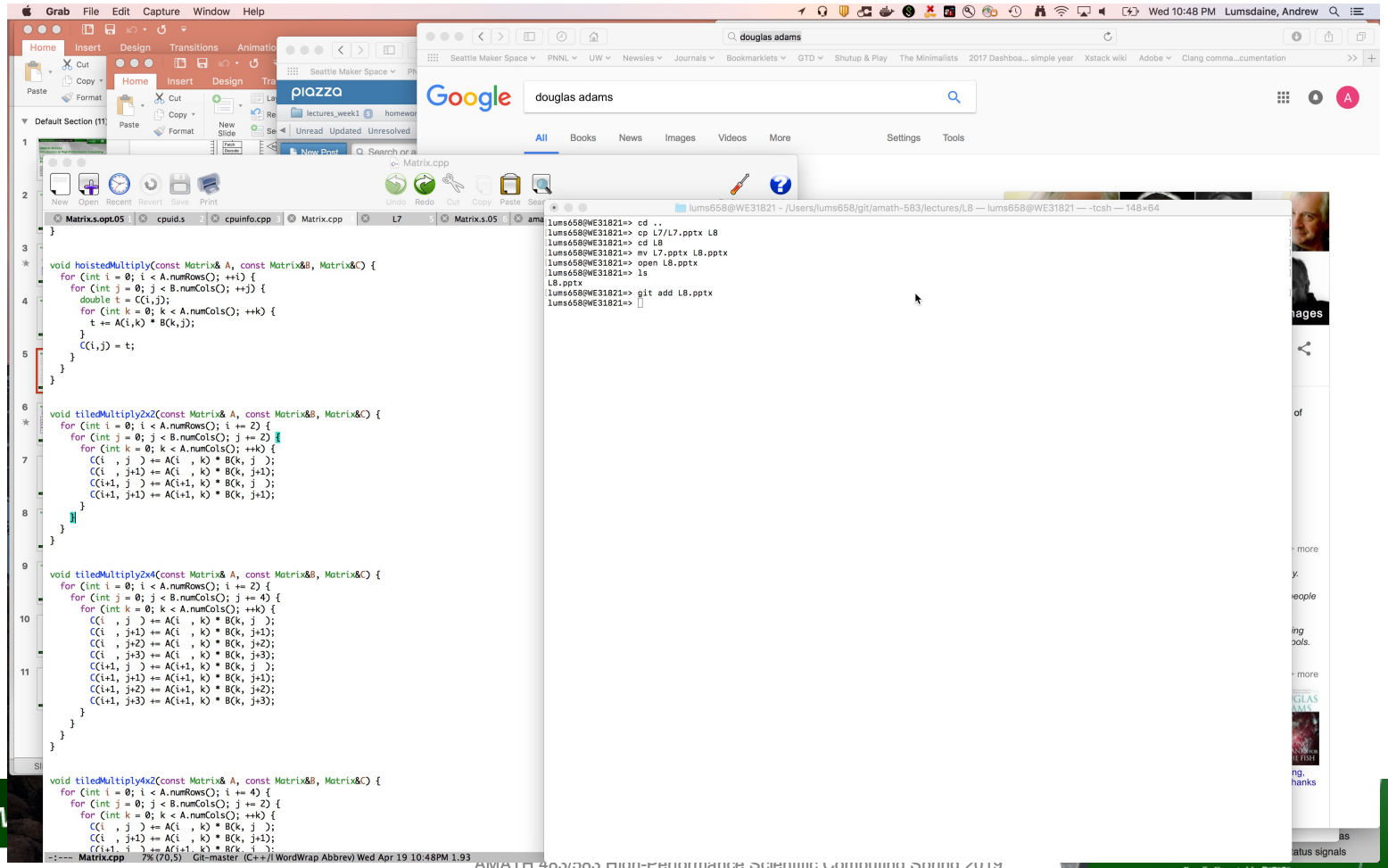
External to OS

OS does not do this

External to OS

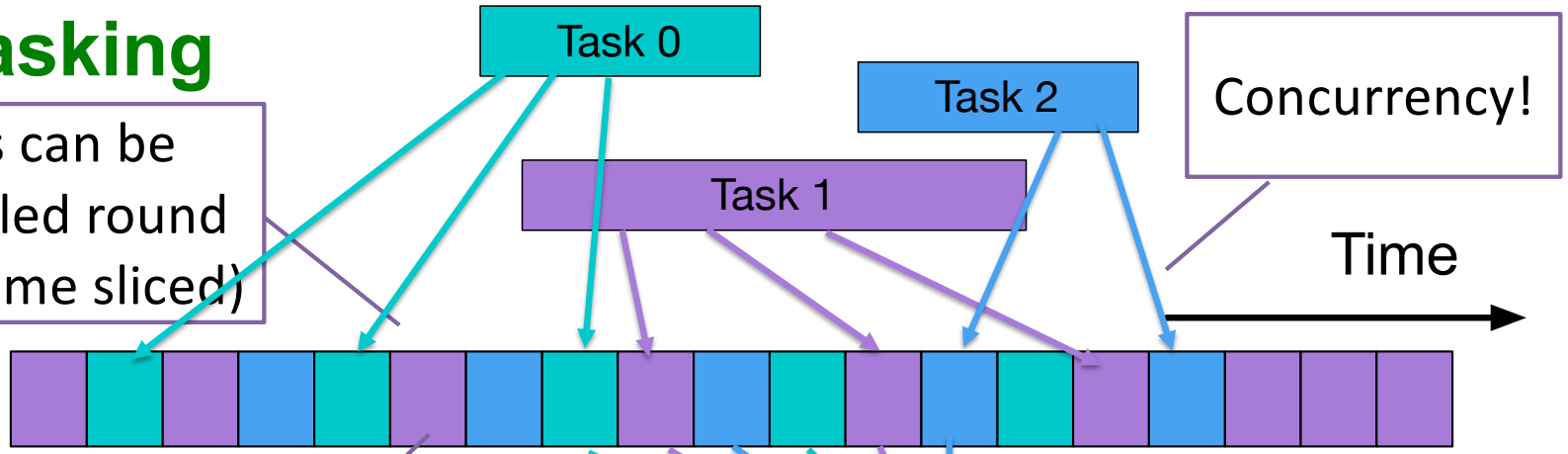
Expensive!

How Do We Run Multiple Programs Concurrently?

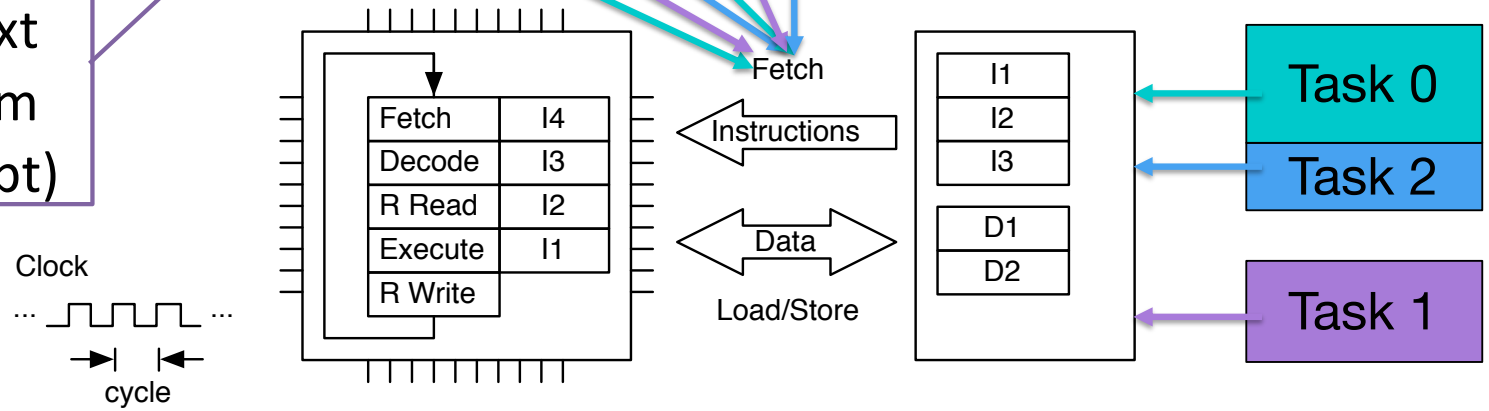


Multitasking

Tasks can be scheduled round robin (time sliced)



Run to context switch (system call or interrupt)

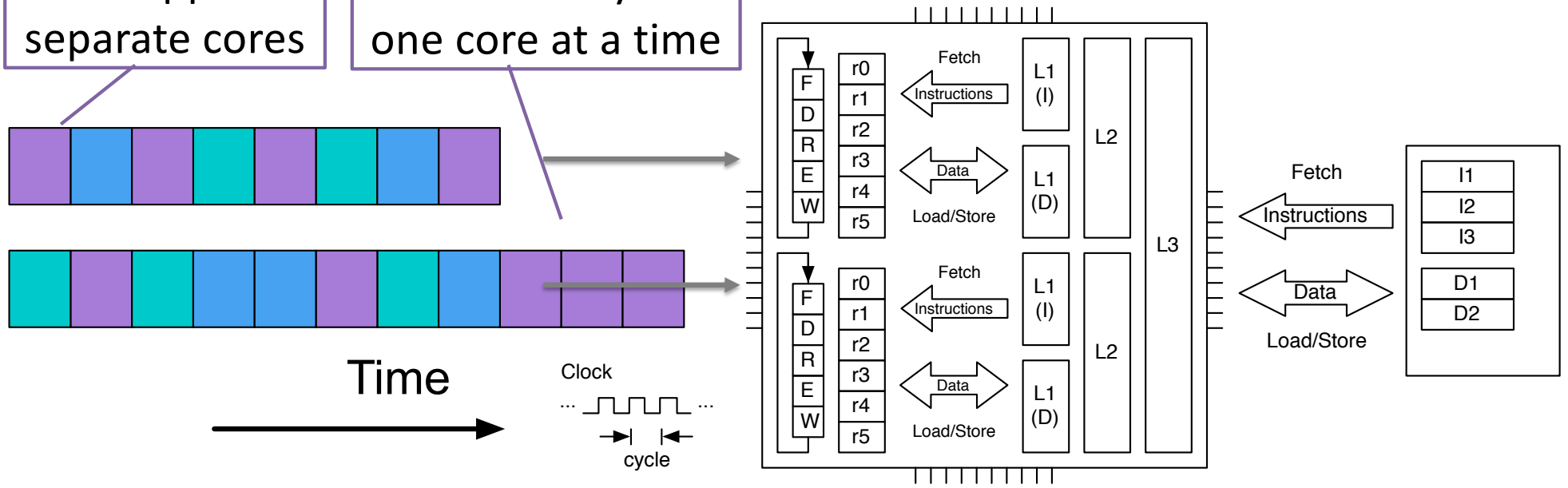


Multitasking on Multicore

Concurrency!

Time sliced and mapped to separate cores

A single threaded task can only use one core at a time



Multitasking on Multicore

Parallelism!

What about L1, L2?

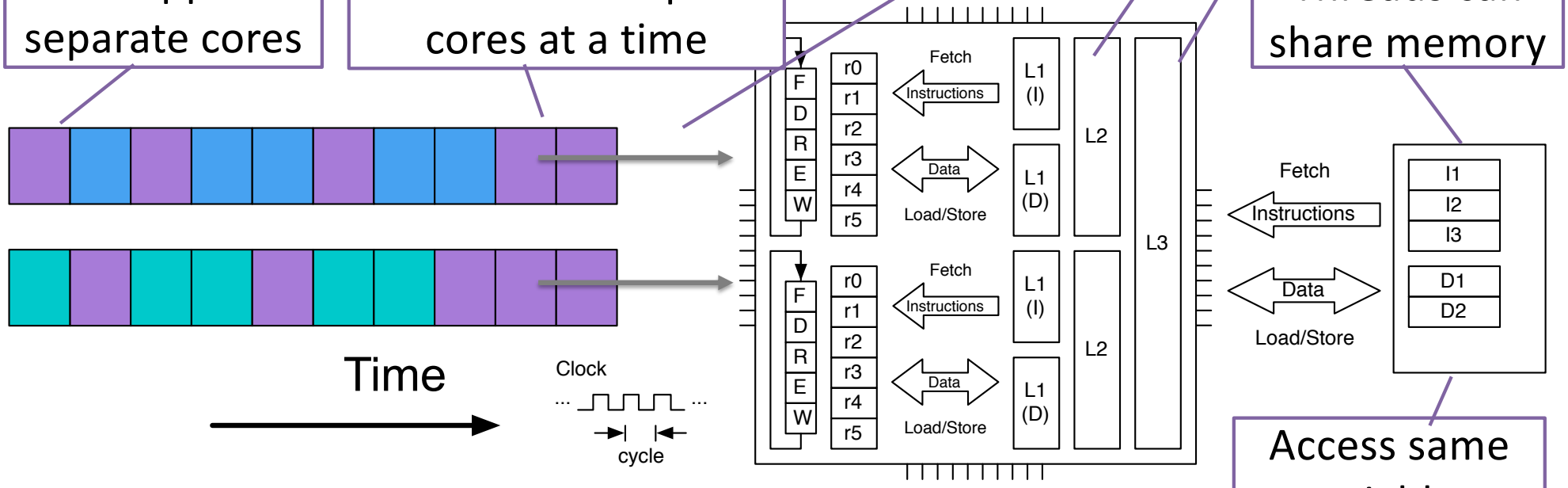
Time sliced and mapped to separate cores

A multithreaded task can use multiple cores at a time

Shorter run time!

And L3 cache

Threads can share memory



Access same variables

Cache Coherence

Hardware managed

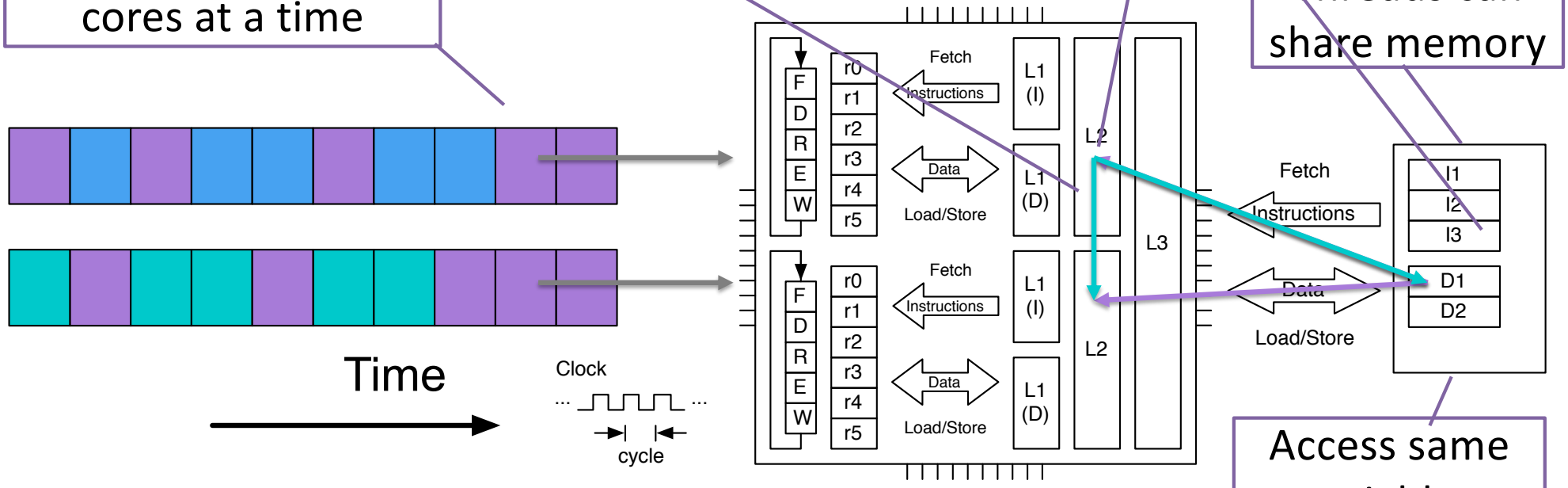
Same variable can be in two different caches

A multithreaded task can use multiple cores at a time

Cache coherence / memory consistency

What if one gets modified?

Threads can share memory



Access same variables

Multitasking on Multicore

Nonetheless, this is the essence of ***parallel*** computing

Parallel computation isn't done until all cores are done

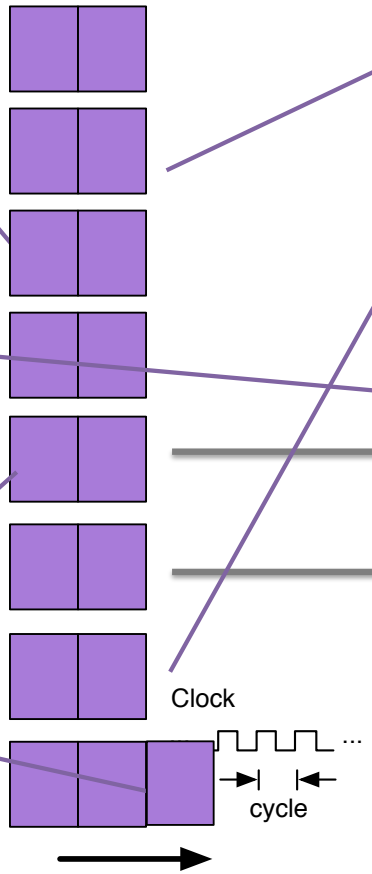
Not the same as concurrent

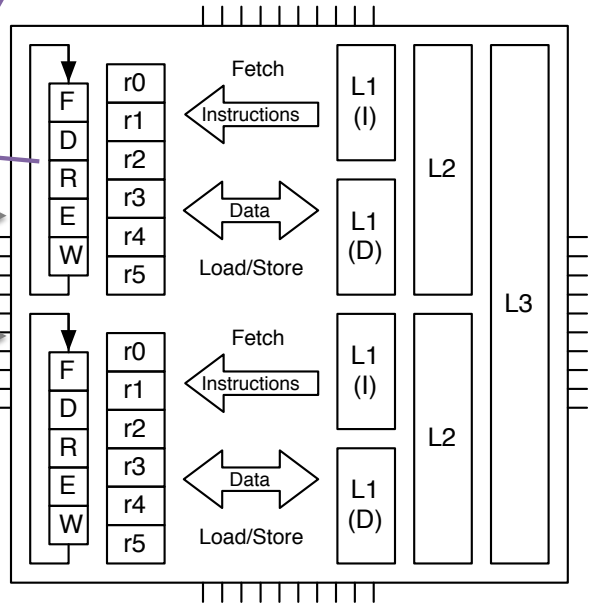
In 1/8 the time (?)

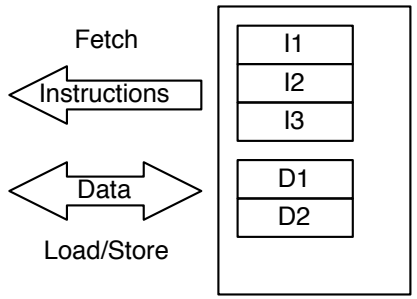
Need enough cores (8)

Work needs to be balanced

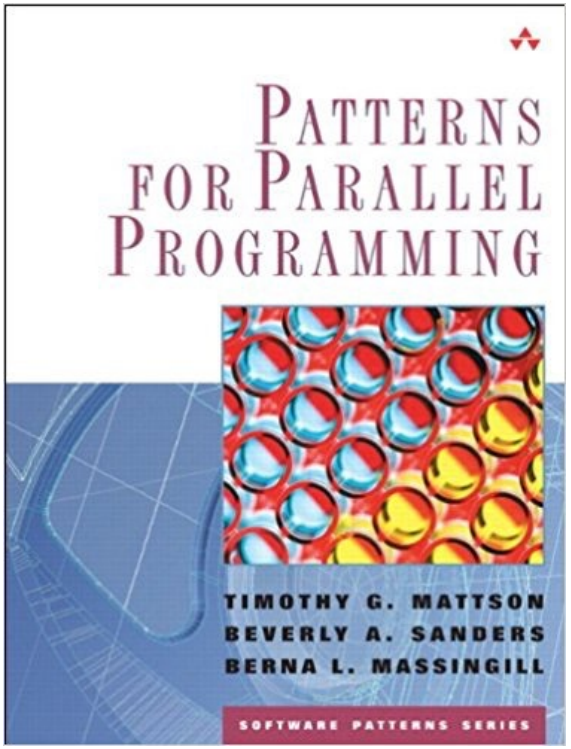
oops



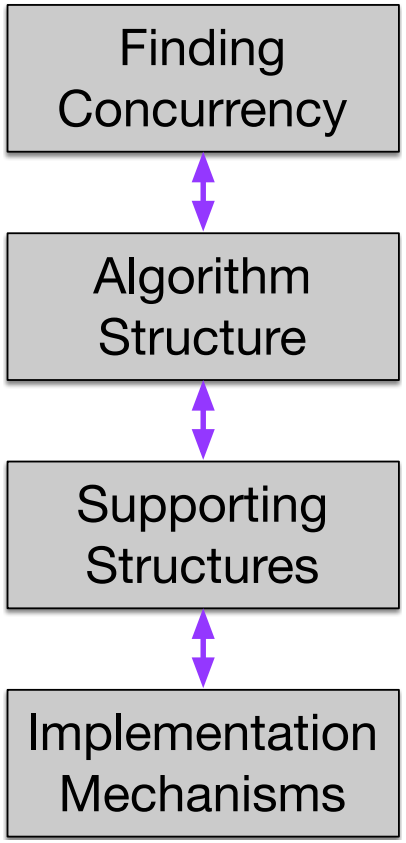




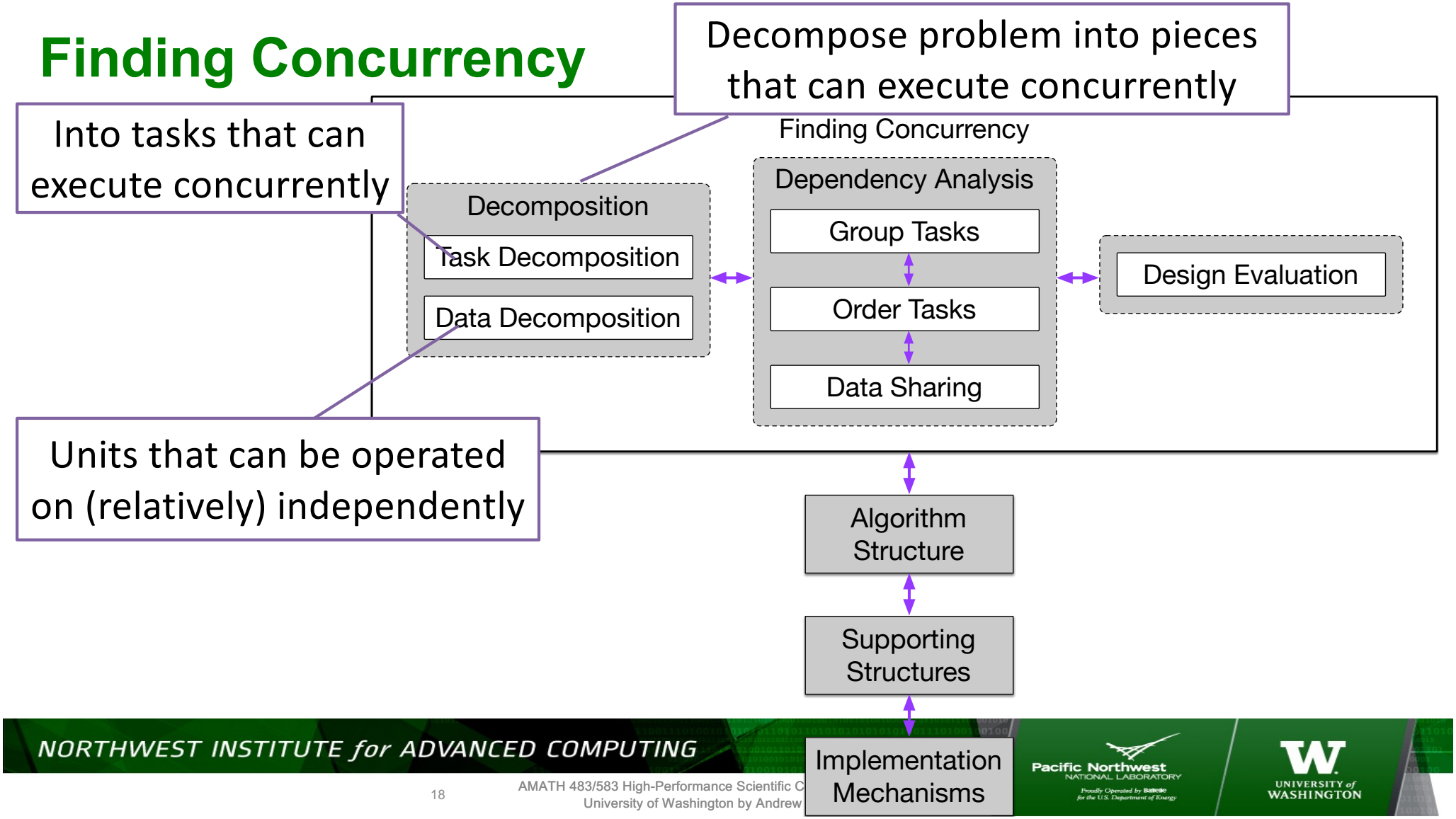
Parallelization Strategy



Timothy Mattson, Beverly Sanders, and Berna Massingill. 2004. *Patterns for Parallel Programming*(First ed.). Addison-Wesley Professional.



Finding Concurrency



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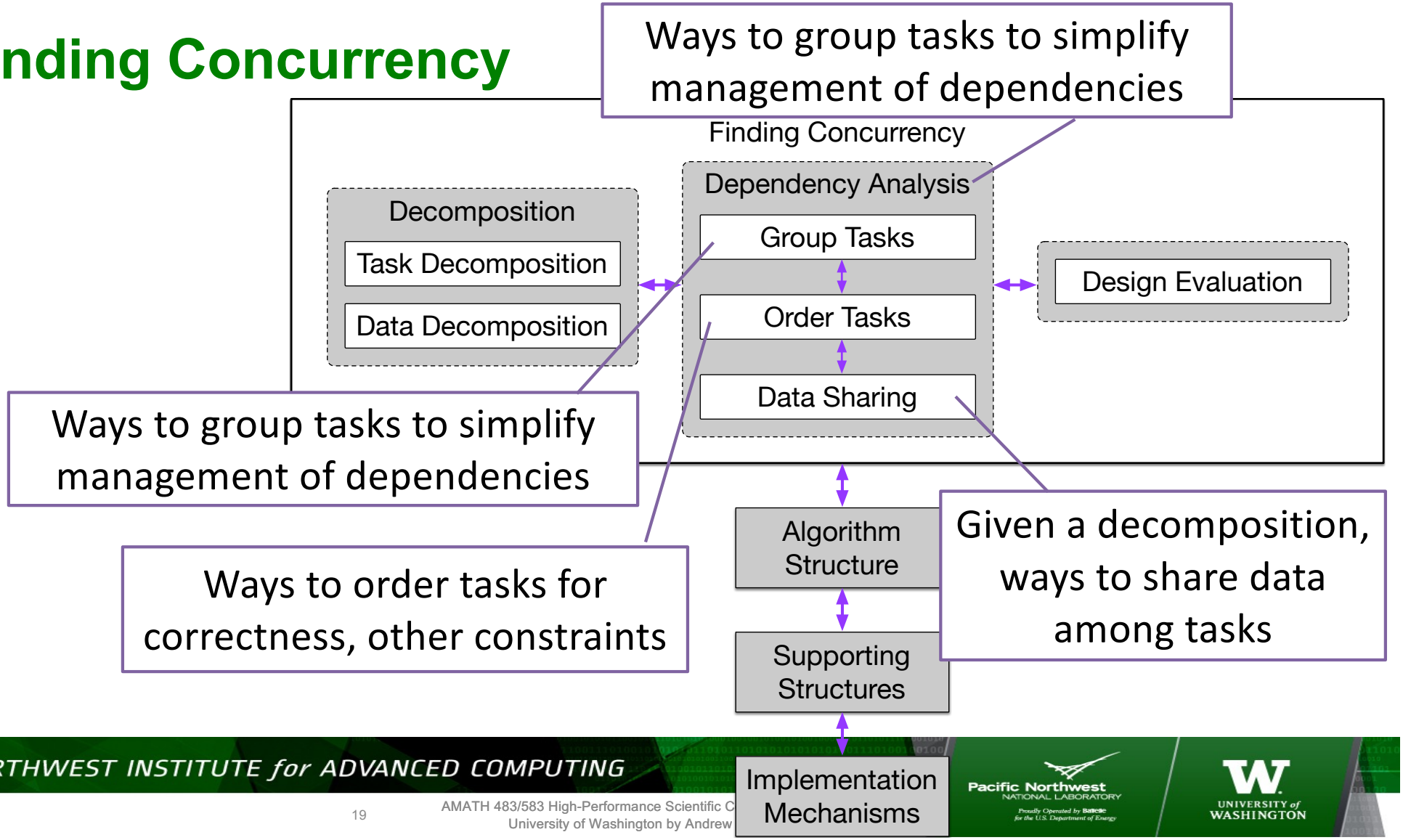
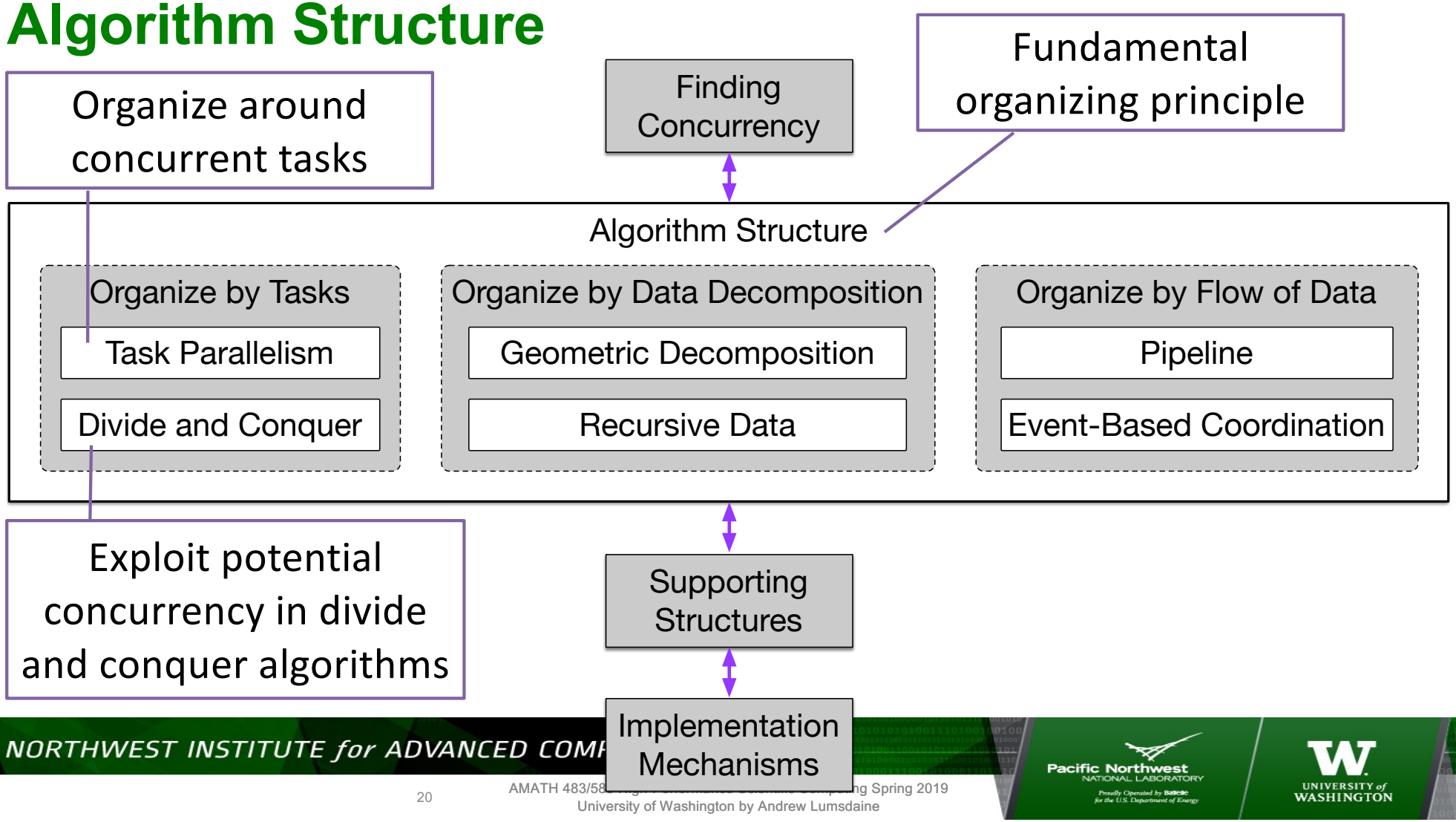


Algorithm Structure



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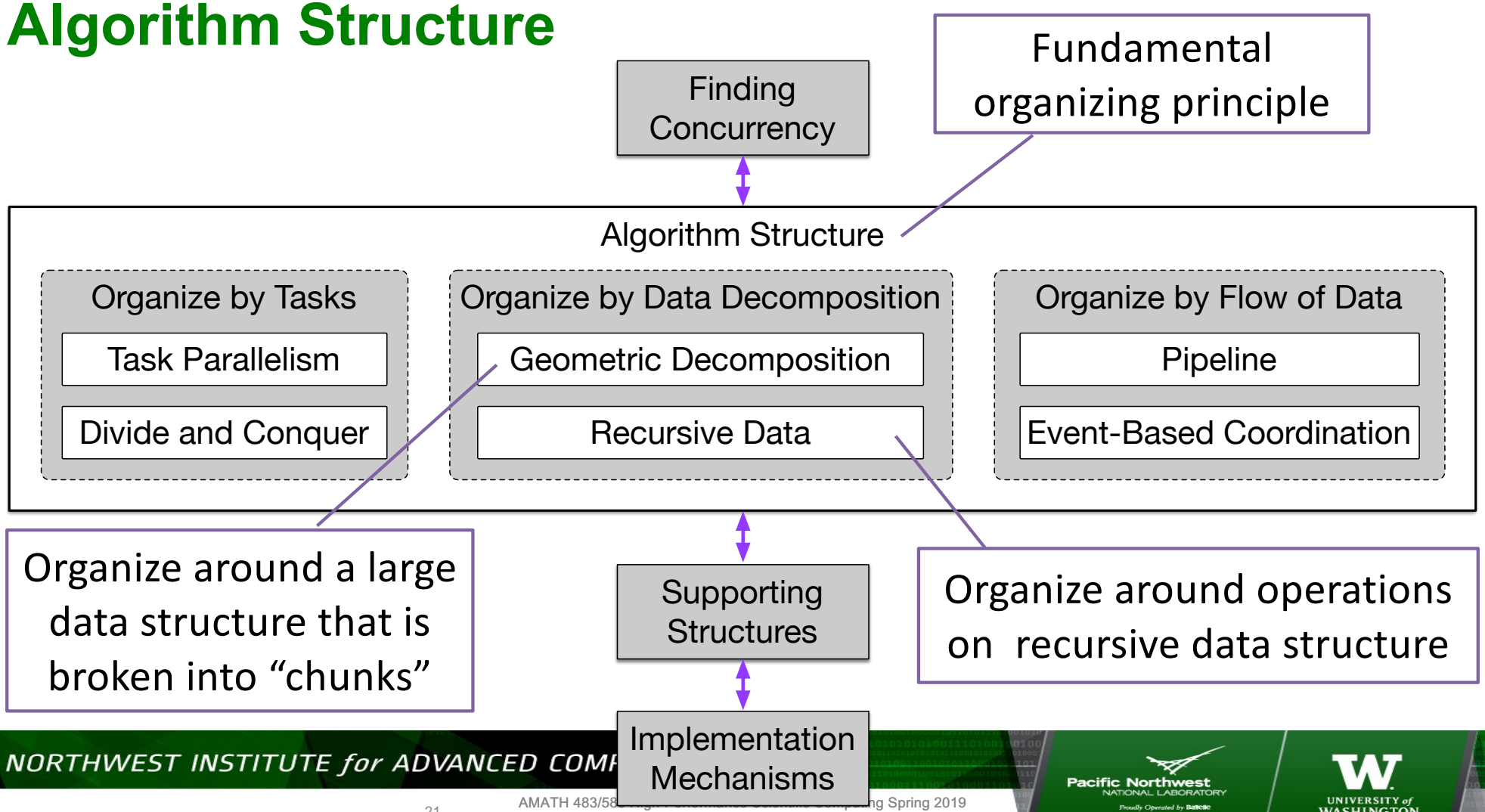

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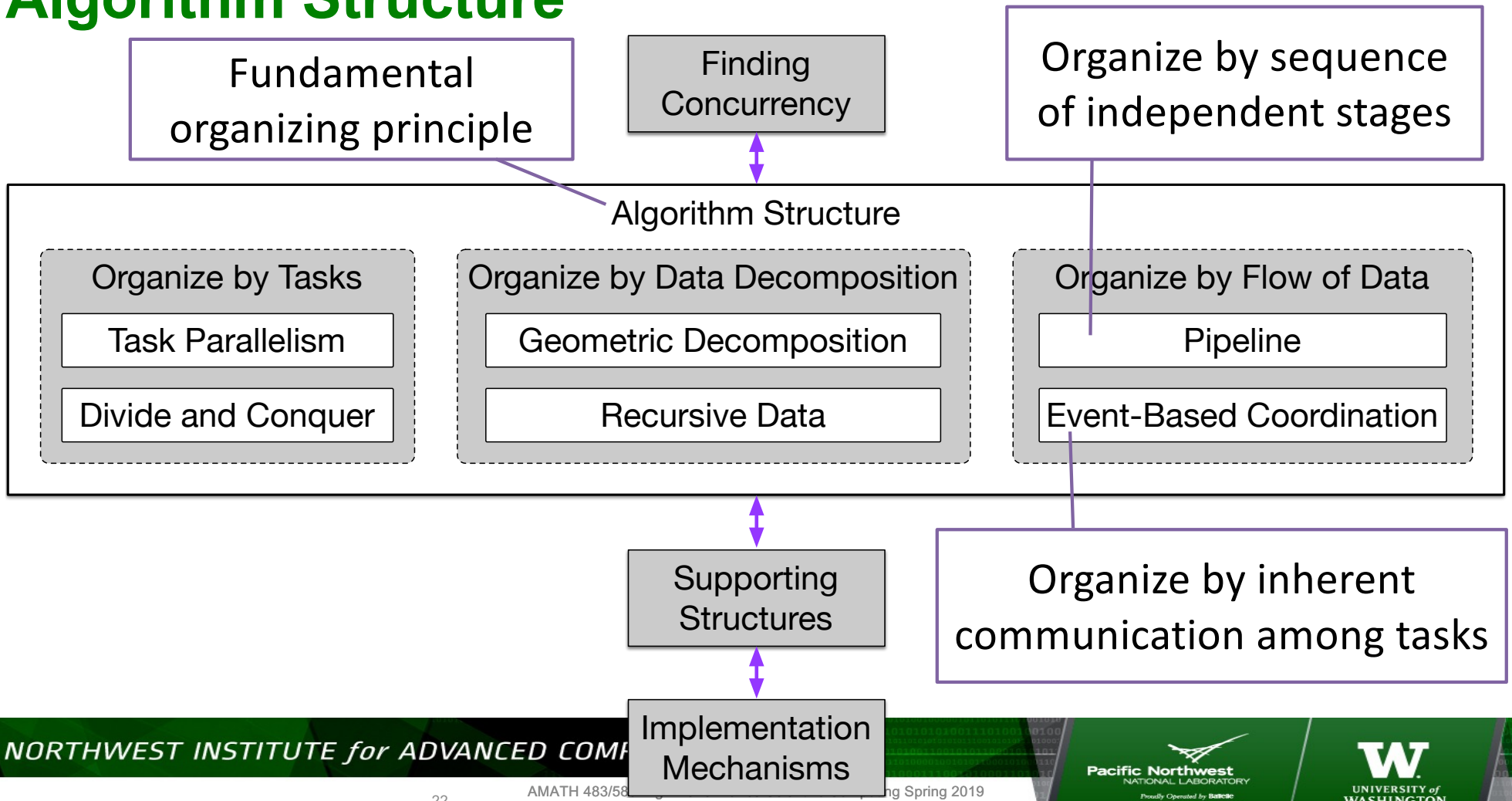
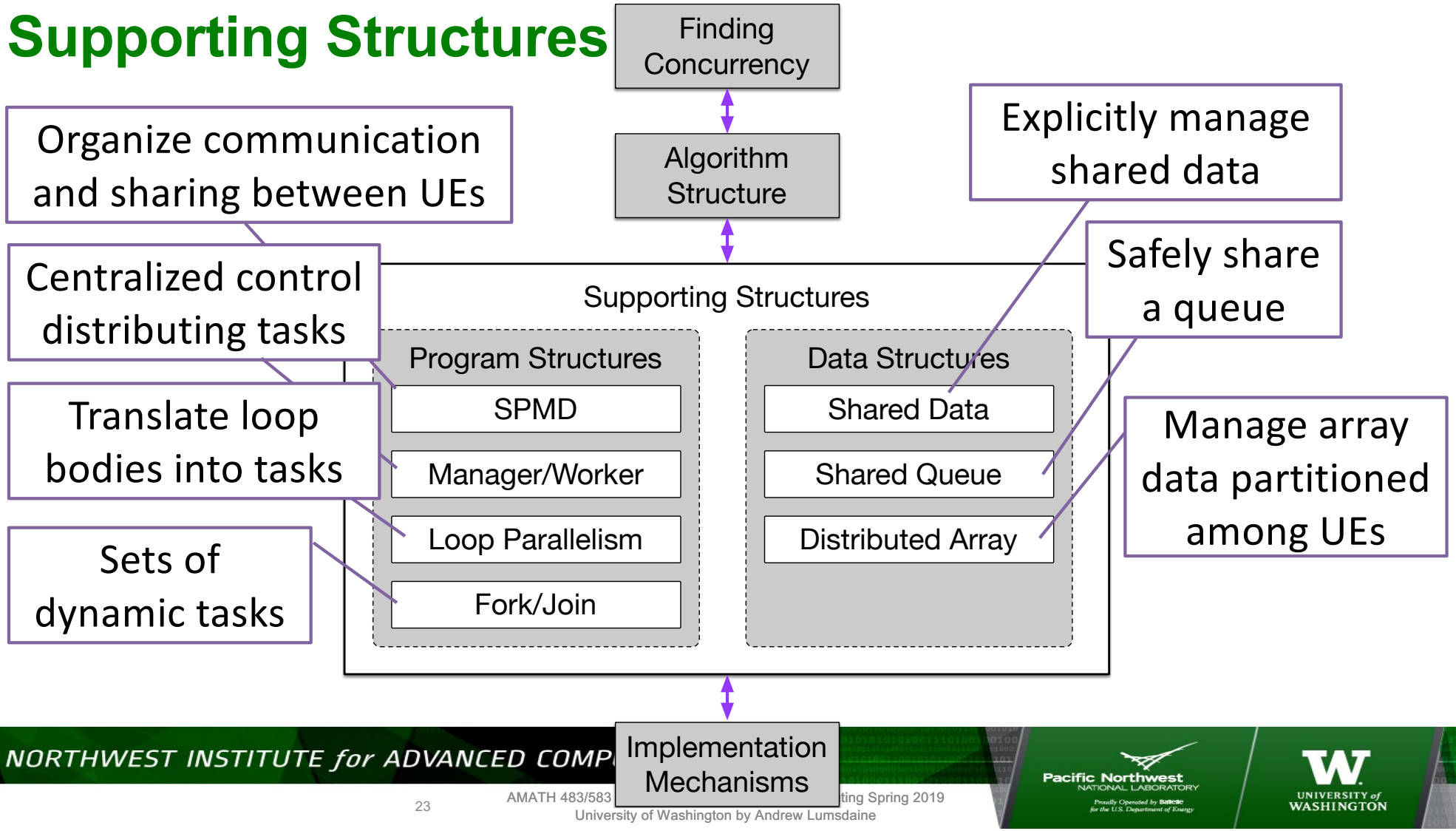
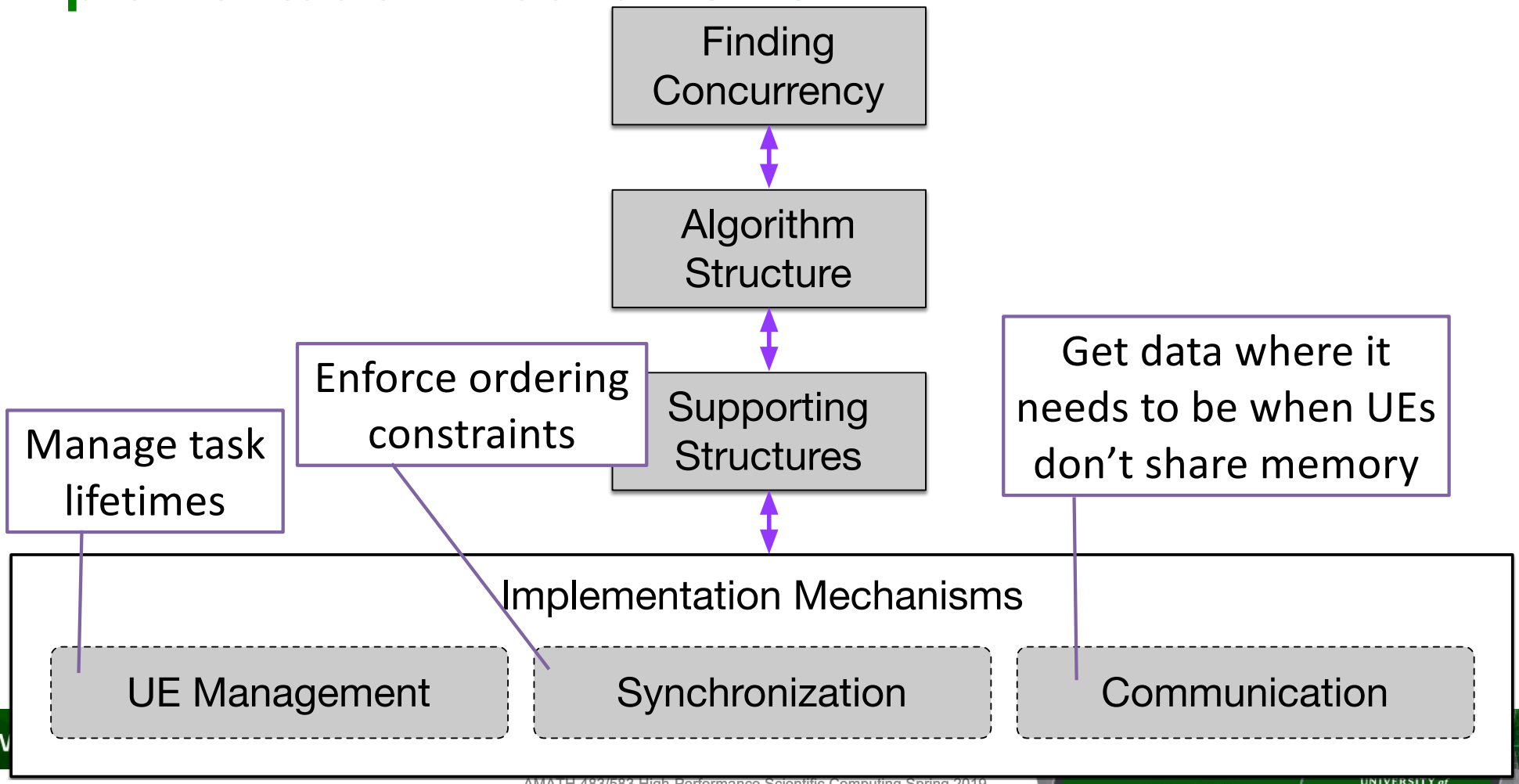


Supporting Structures



Implementation Mechanisms

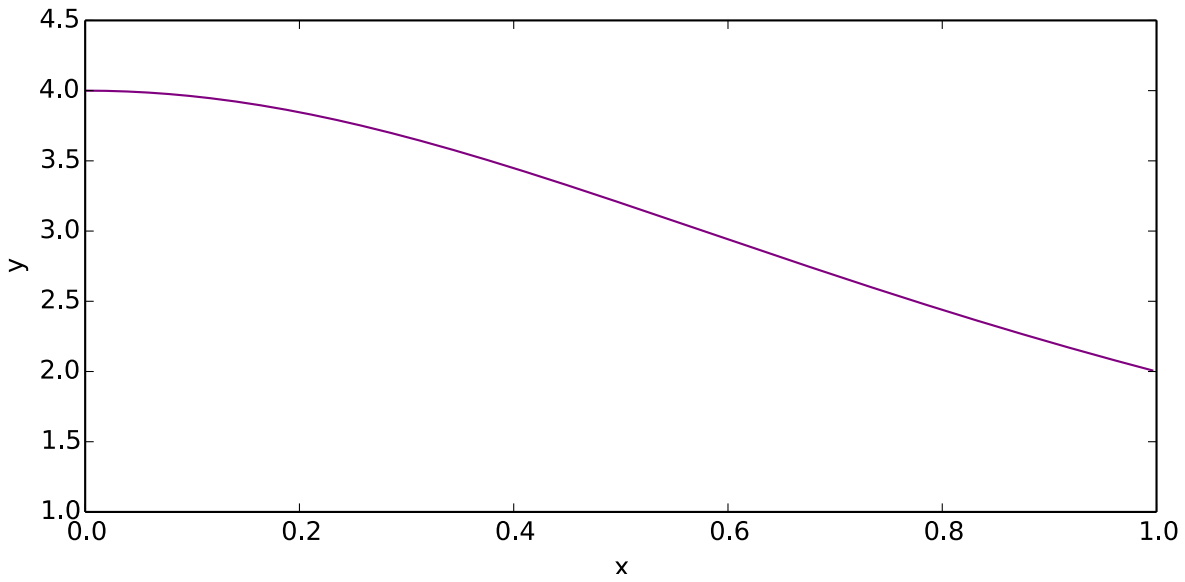


Example

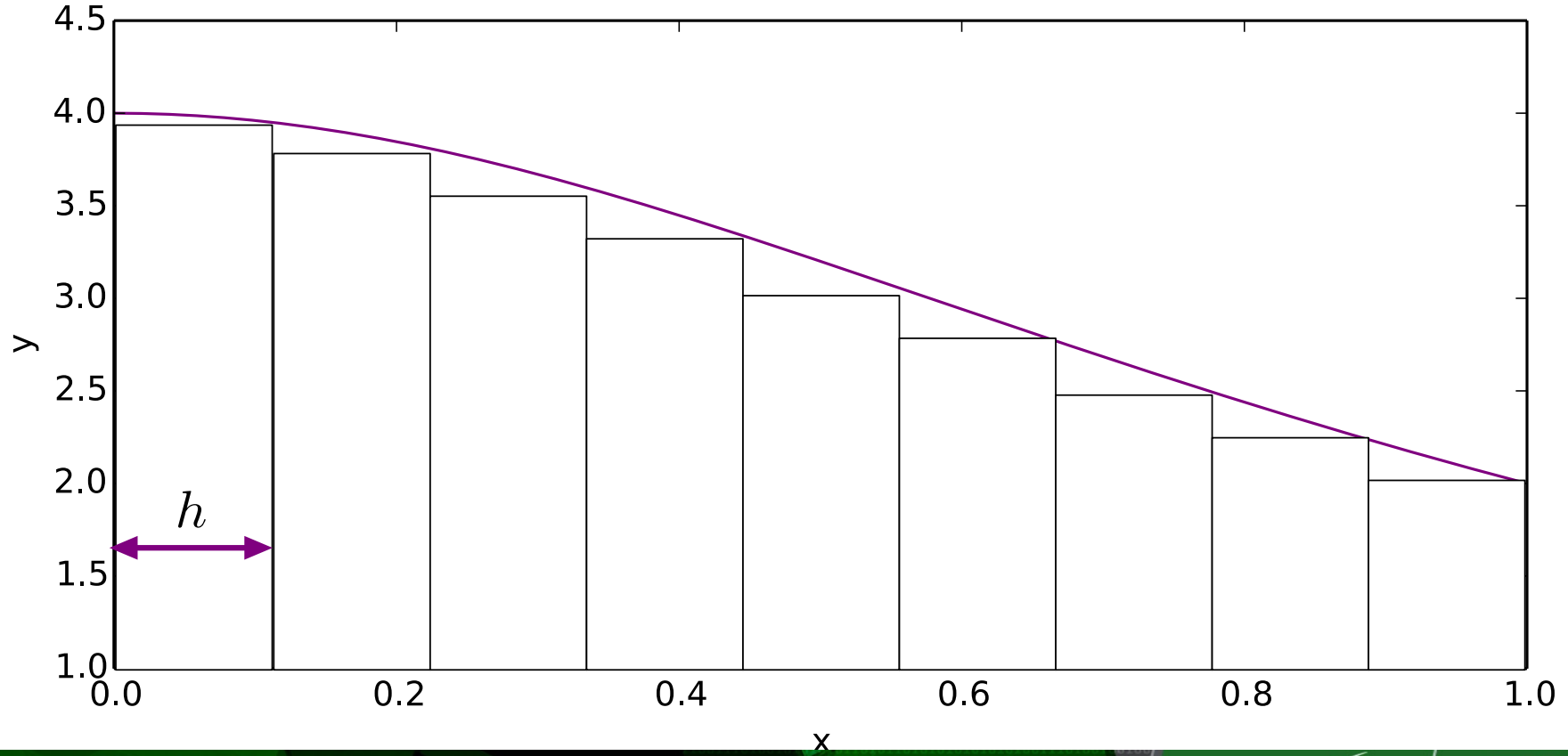
- Find the value of π

- Using formula

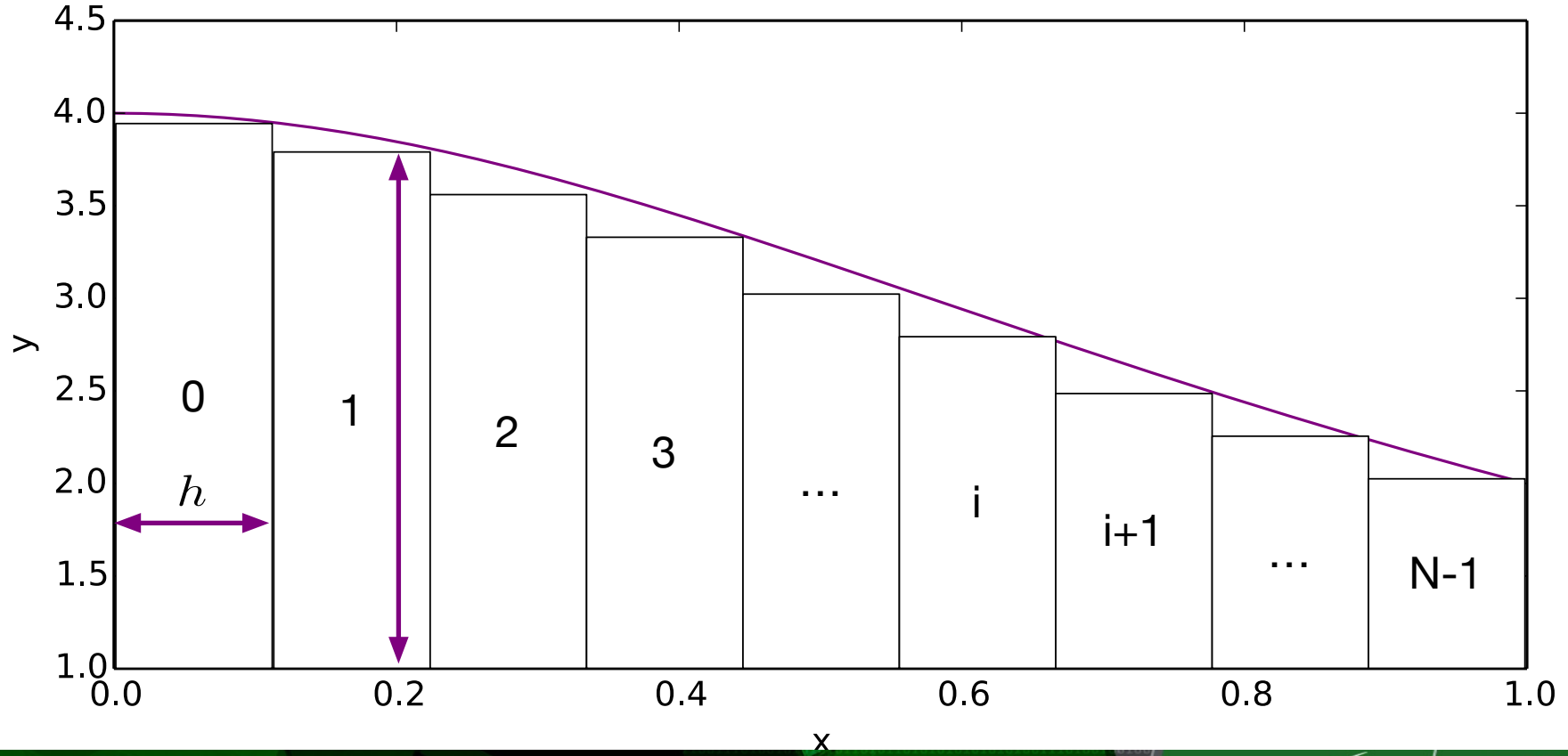
$$\pi = \int_0^1 \frac{4}{1+x^2} dx$$



Discretization



Numerical Quadrature



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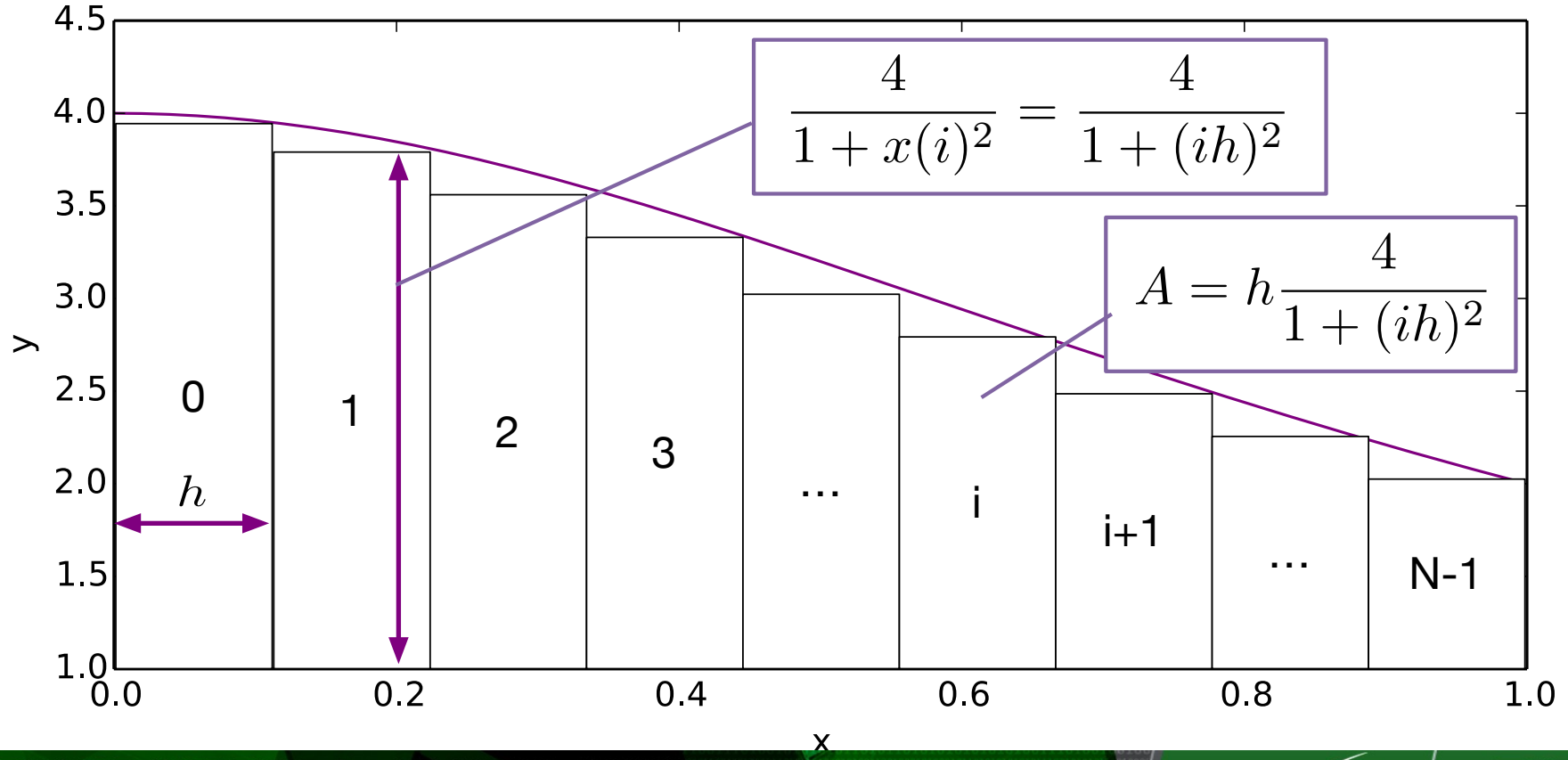

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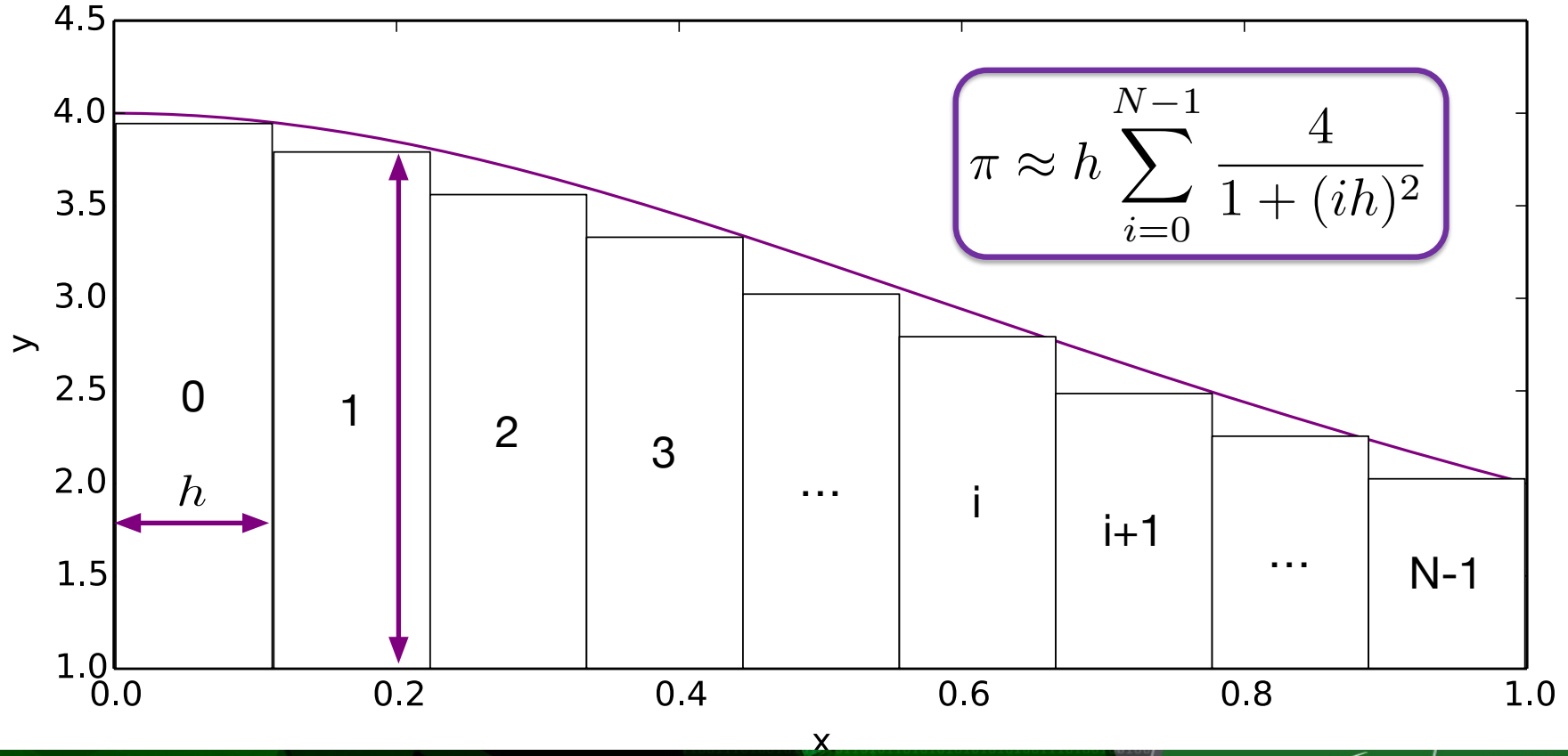

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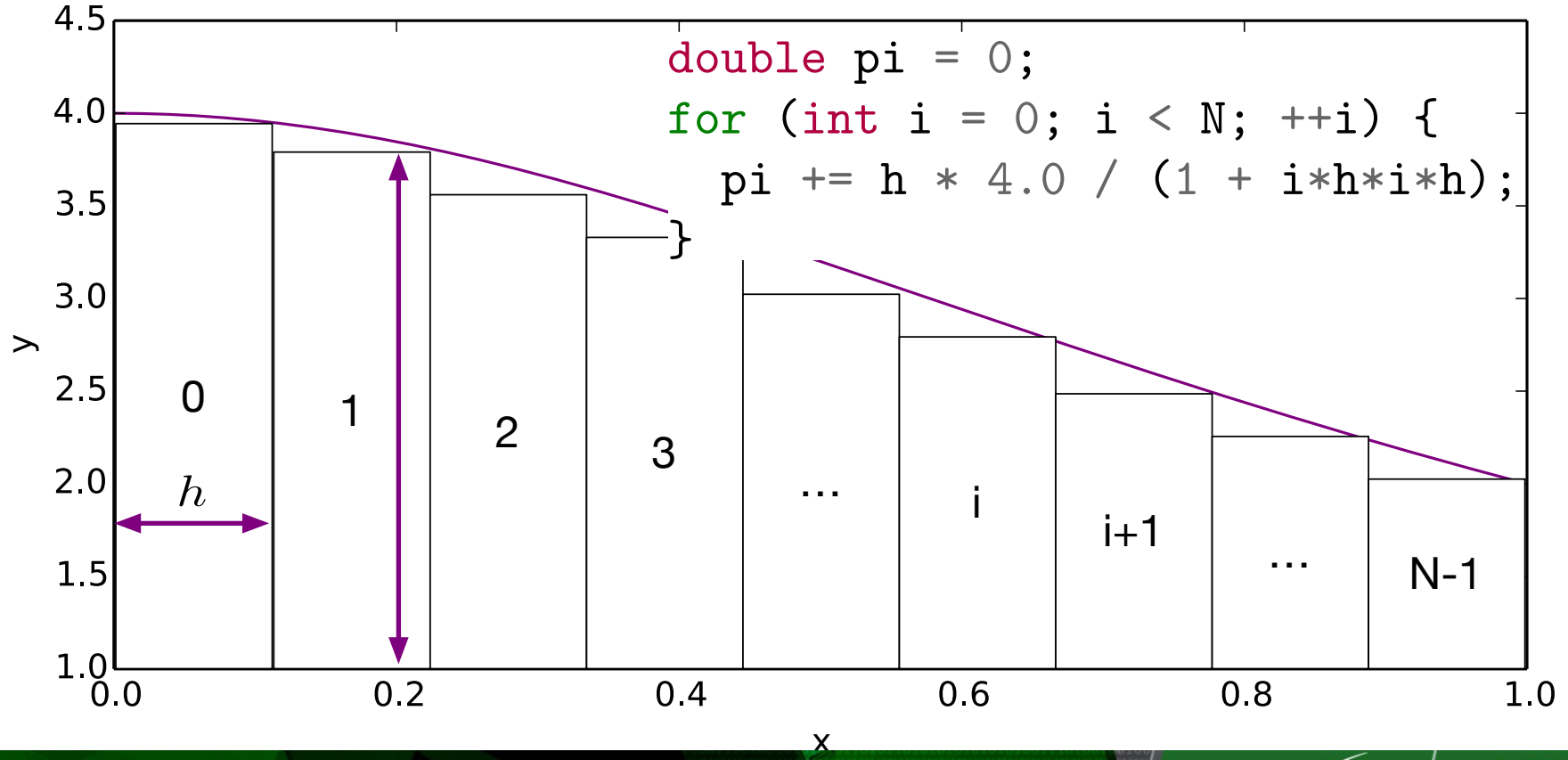

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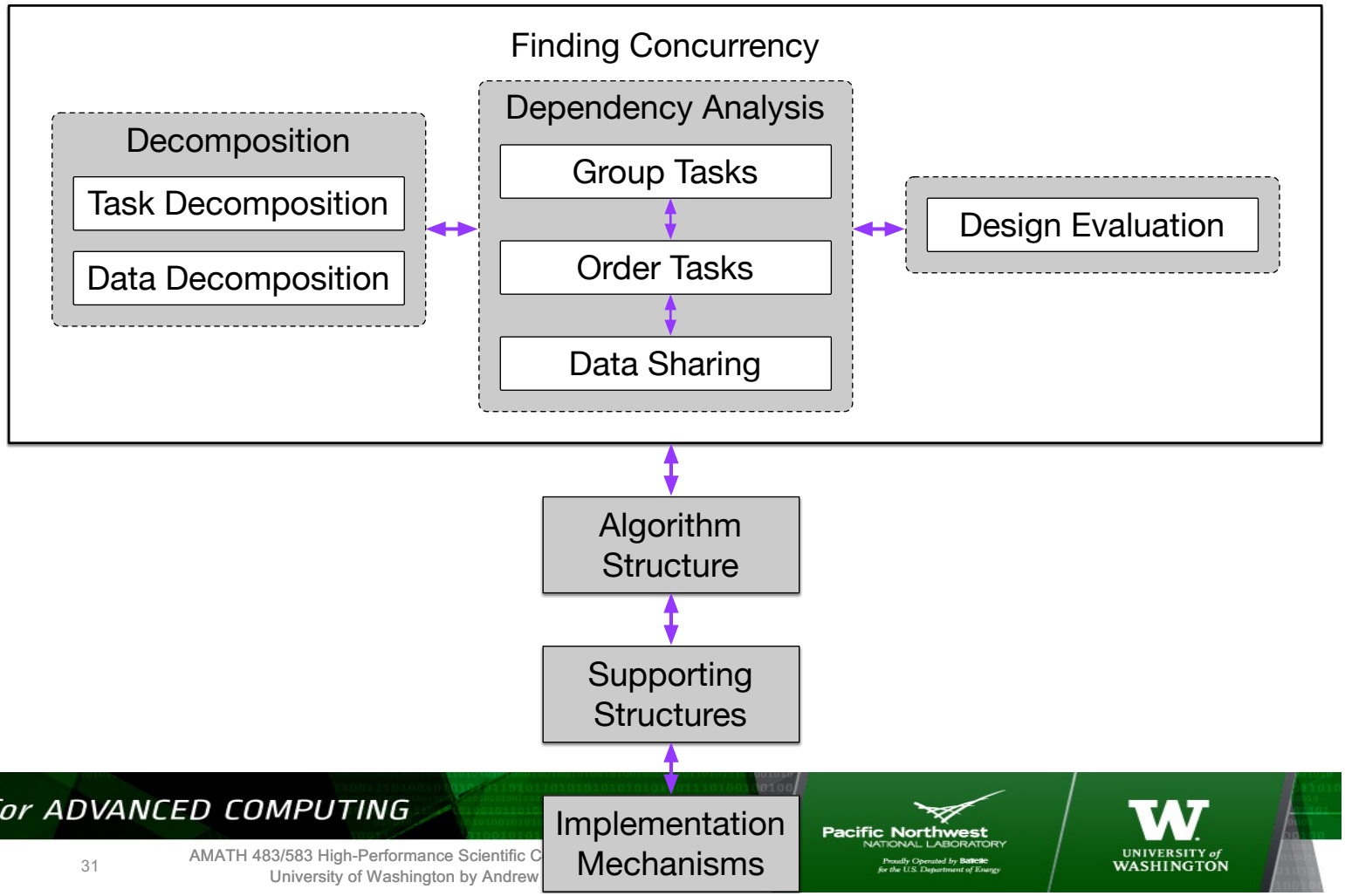

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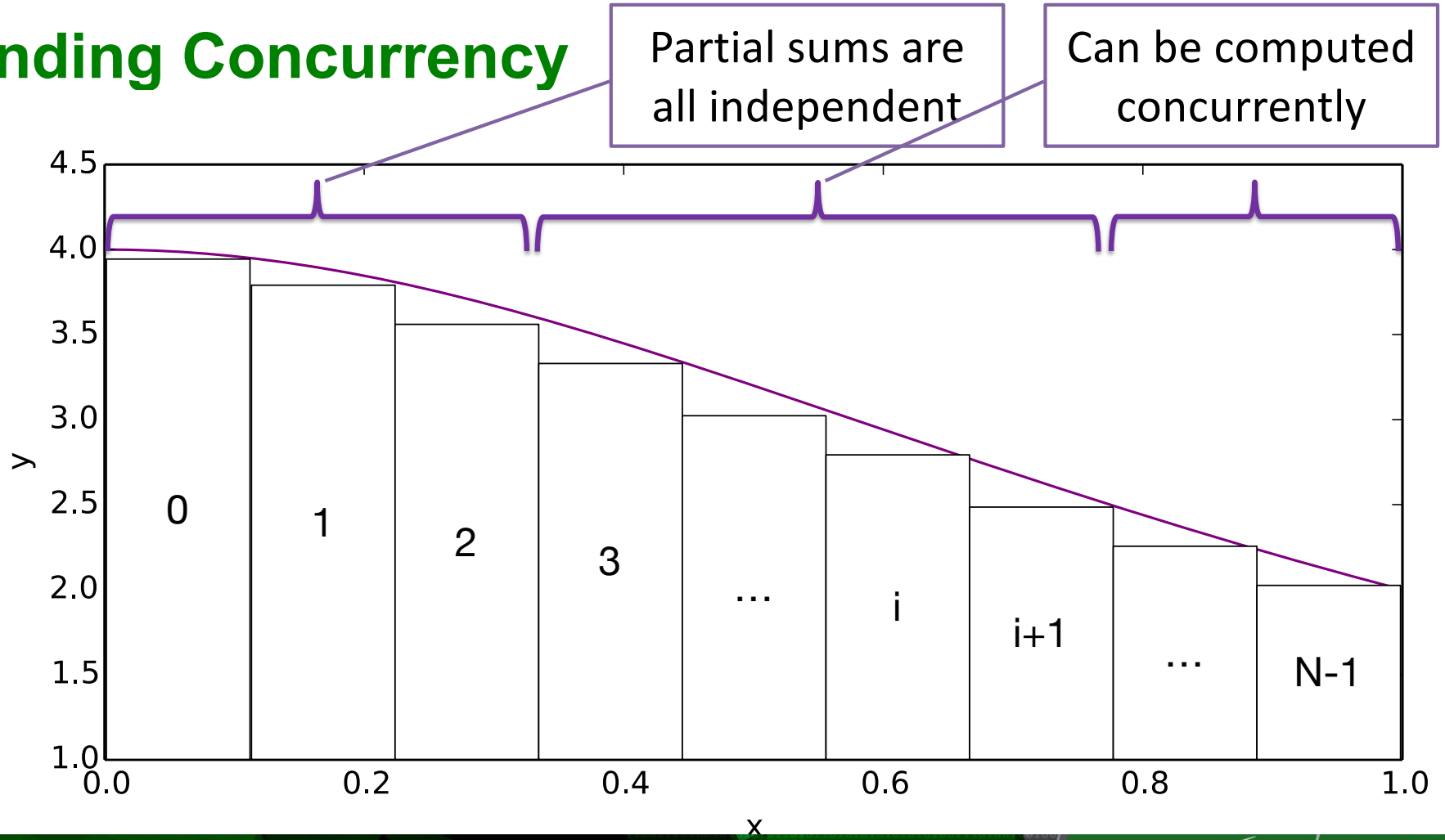

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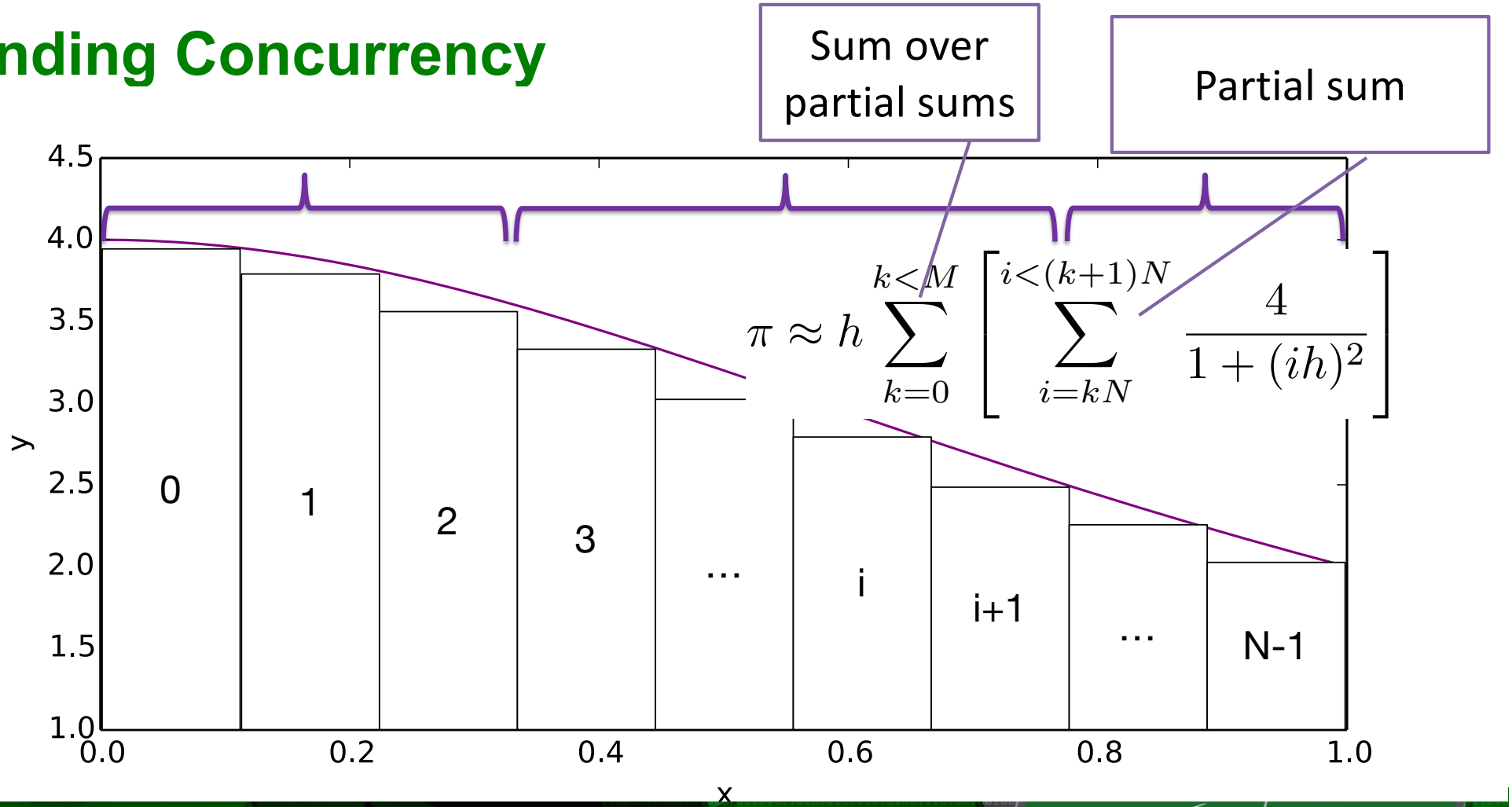

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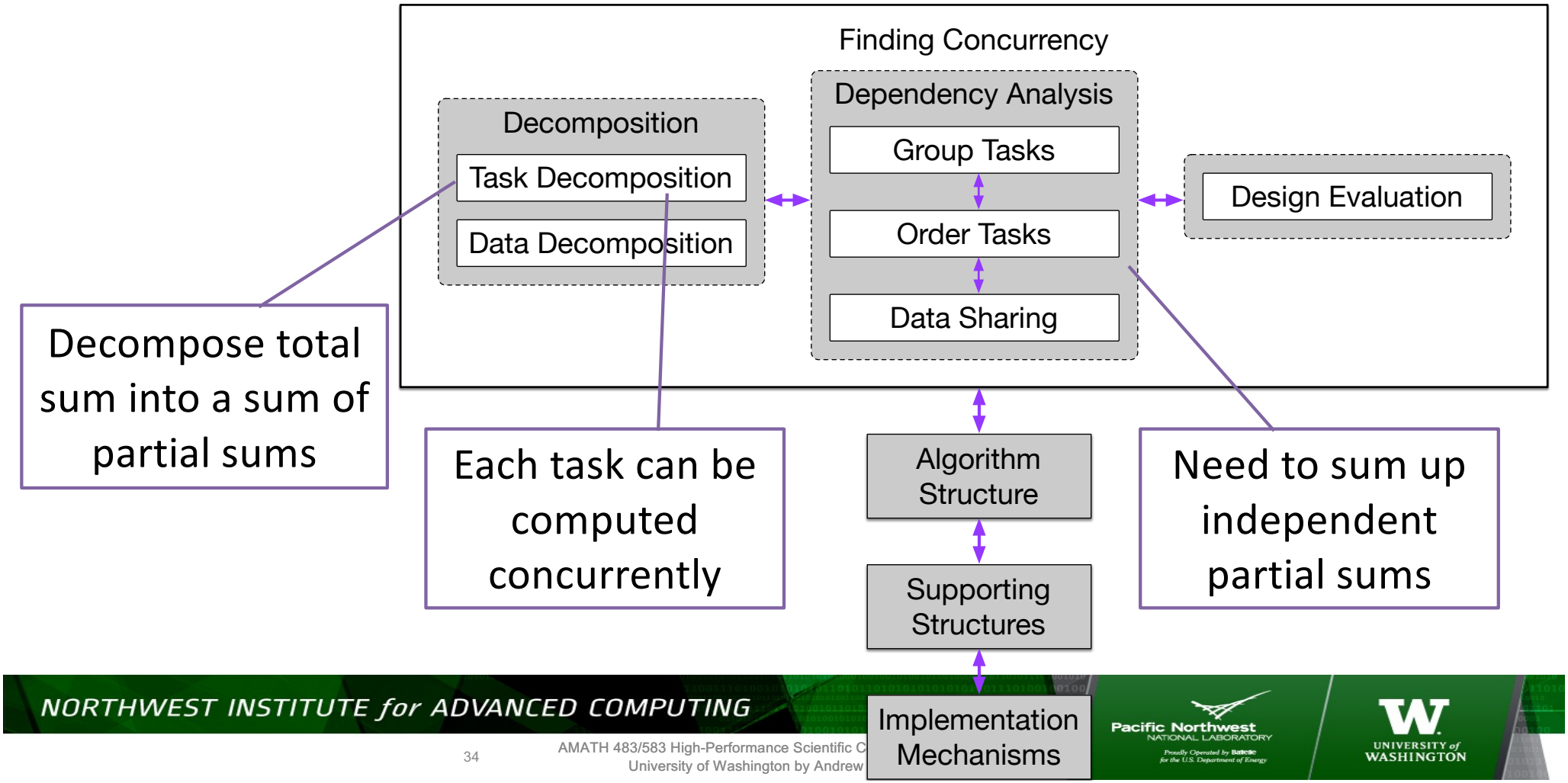

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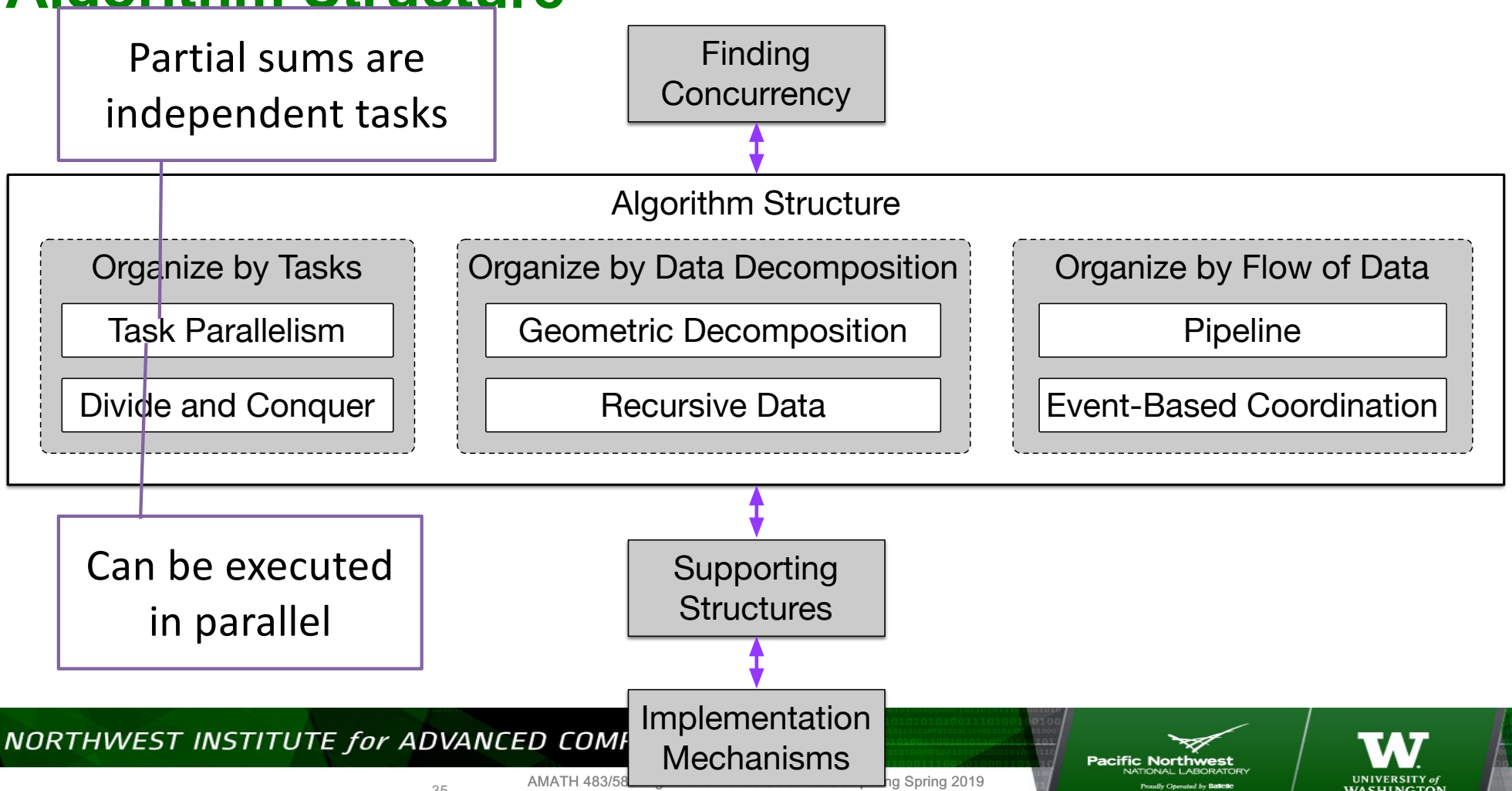

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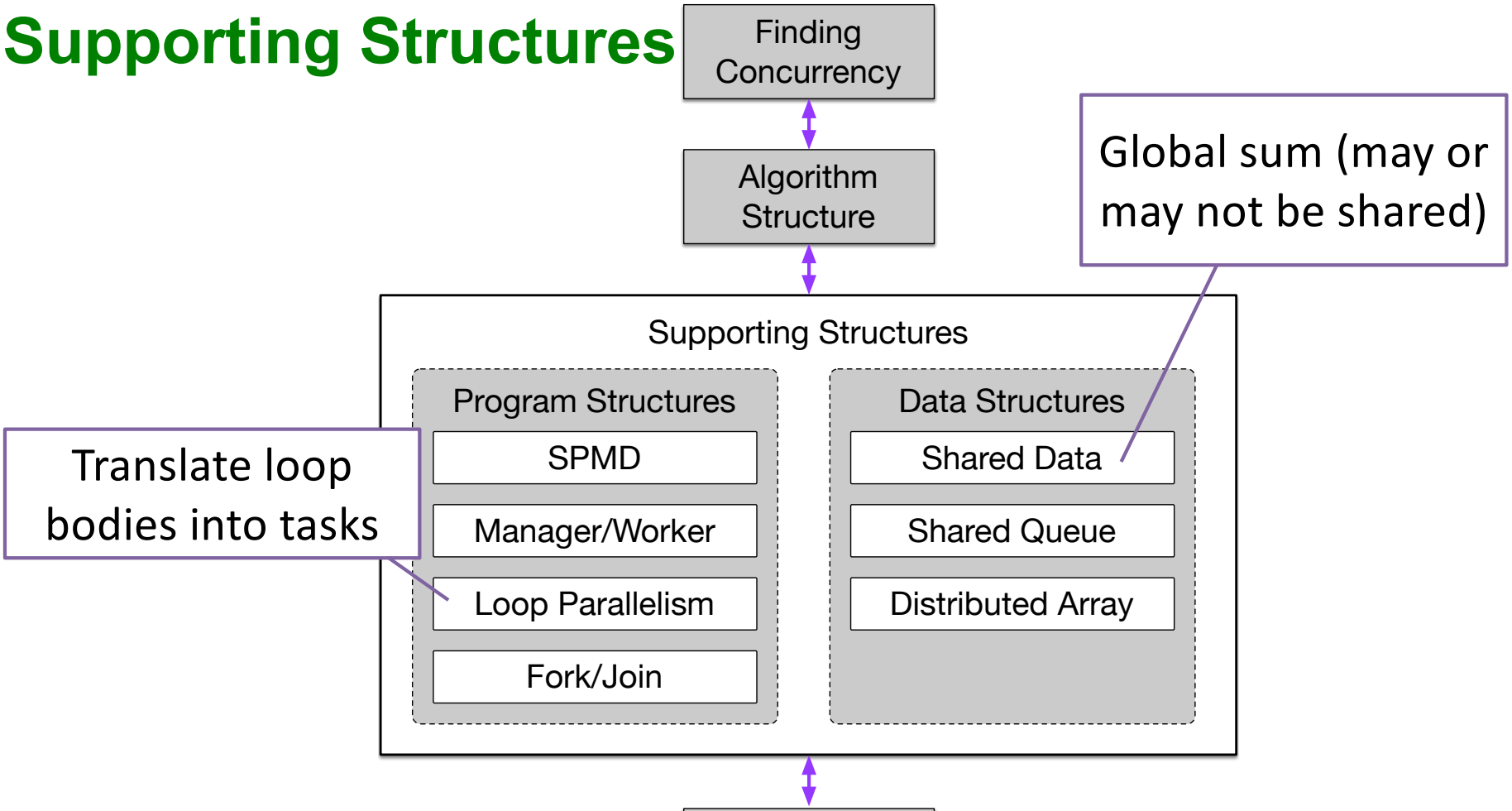

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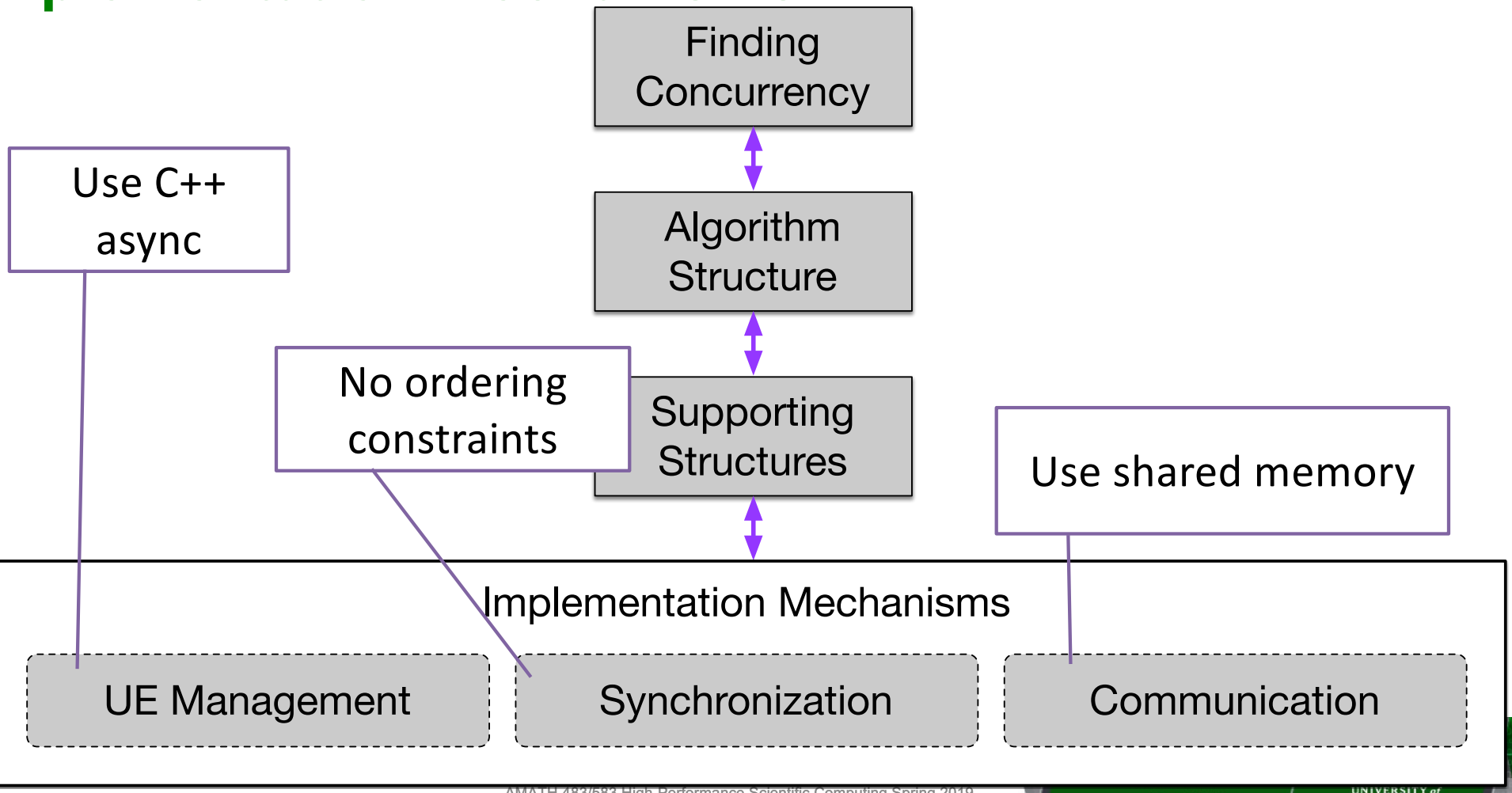


Sequential Implementation (Two Nested Loops)

```
double h = 1.0 / (double) intervals;

double pi = 0.0;
for (int k = 0; k < intervals; k += blocksize) {
  double partial_pi = 0.0;
  for (int i = k; i < (k+blocksize); ++i) {
    partial_pi += 4.0 / (1.0 + (i*h*i*h));
  }
  pi += h * partial_pi;
}
```

Discretization

For each set of discretized points

Compute partial sum

Accumulate final sum

Threads vs Tasks

```
void sayHello(int tnum) {
  cout << "Hello World.  I am thread " << tnum << endl;
}

int main() {
  std::thread tid[16];

  for (int i = 0; i < 16; ++i)
    tid[i] = thread (sayHello, i);

  for (int i = 0; i < 16; ++i)
    tid[i].join();

  return 0;
}
```

Task

Launch threads

"fork"

Wait for tasks to finish

"join"

Threads

Thread returns void

Oops

How do we get partial sums?

How do we update global total?

```
void partial_pi(unsigned long begin, unsigned long end) {
  double partial_pi = 0.0;
  for (unsigned long i = begin; i < end; ++i) {
    partial_pi += 4.0 / (1.0 + (i*h*i*h));
  }
  return partial_pi;
}

int
main(int argc, char *argv[])
{
  double h = 1.0 / (double) intervals;

  double pi = 0.0;
  for (int k = 0; k < intervals; k += blocksize) {

    pi += h * partial_pi;
  }
  std::cout << "pi is approximately " << pi << std::endl;

  return 0;
}
```

Threads

Task

Assign task to thread

```
void partial_pi(unsigned long begin, unsigned long end, double h, double& pi) {
  double partial_pi = 0.0;
  for (unsigned long i = begin; i < end; ++i) {
    partial_pi += 4.0 / (1.0 + (i*h*i*h));
  }
  pi += h*partial_pi;
}

int
main(int argc, char *argv[])
{
  std::vector<std::thread> threads;

  double h = 1.0 / (double) intervals;

  double pi = 0.0;
  for (unsigned long k = 0; k < num_blocks; ++k) {
    threads.push_back(std::thread(partial_pi,
        k*blocksize, (k+1)*blocksize, h, std::ref(pi)));
  }

  for (unsigned long k = 0; k < num_blocks; ++k) {
    threads[k].join();
  }
  std::cout << "pi is approximately " << pi << std::endl;

  return 0;
}
```

Threads

Local variable

Shared variable

```
void partial_pi(unsigned long begin, unsigned long end, double h, double& pi) {
  double partial_pi = 0.0;
  for (unsigned long i = begin; i < end; ++i) {
    partial_pi += 4.0 / (1.0 + (i*h*i*h));
  }
  pi += h*partial_pi;
}
```

Update shared variable

Threads

```
int main(int argc, char *argv[]) {
  double h = 1.0 / (double) intervals;

  std::vector<std::thread> threads;

  double pi = 0.0;
  for (unsigned long k = 0; k < num_blocks; ++k) {
    threads.push_back(
      std::thread(
        partial_pi, k*blocksize, (k+1)*blocksize, h, std::ref(pi)));
  }

  for (unsigned long k = 0; k < num_blocks; ++k) {
    threads[k].join();
  }
  std::cout << "pi is approximately " << pi << std::endl;

  return 0;
}
```

Container for created threads

Thread constructor

Function that will be the task

Arguments to the function

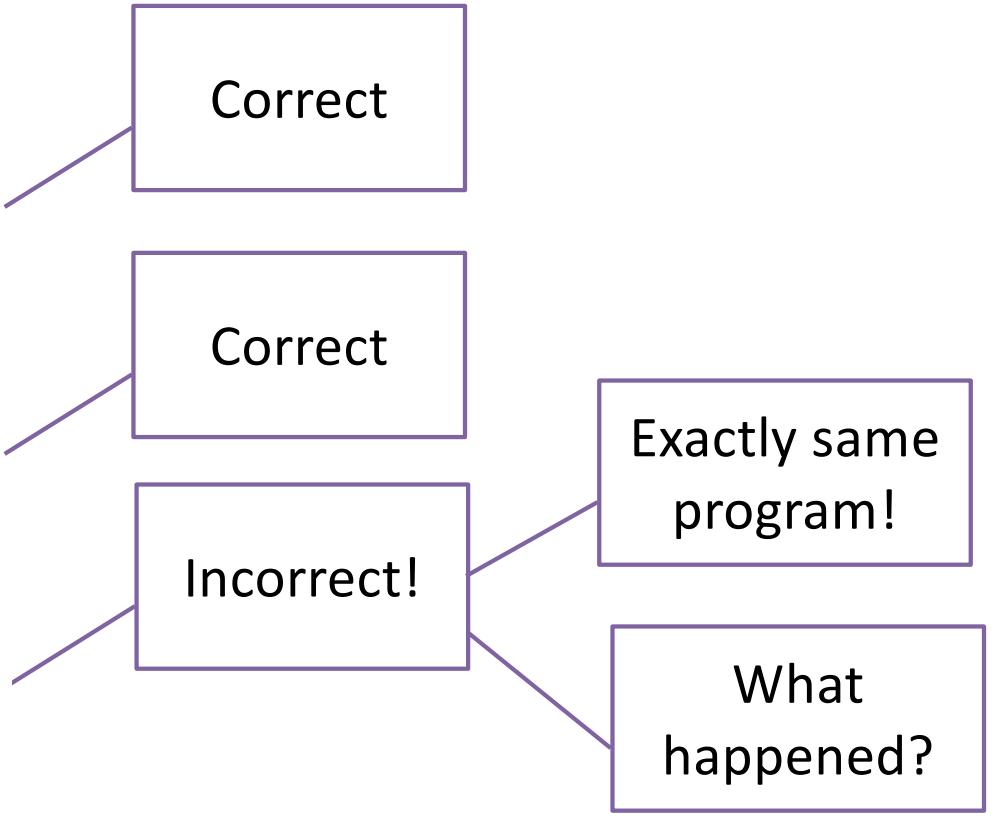
Have to explicitly tag this as a reference

We are invoking std::thread, not partial pi

Results

```
$ ./thrpi
pi is approximately 3.14159

$ ./thrpi
pi is approximately 3.14159
```



Name This Famous Couple

Bonnie and Clyde Use ATMs

```
int bank_balance = 300;

void withdraw(const string& msg, int amount) {
  int bal = bank_balance;
  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance = bal - amount;
}

int main() {
  cout << "Starting balance is " << bank_balance << endl;

  thread bonnie(withdraw, "Bonnie", 100);
  thread clyde(withdraw, "Clyde", 100);

  bonnie.join();
  clyde.join();

  cout << "Final bank balance is " << bank_balance << endl;

  return 0;
}
```

Withdraw Function

```
int bank_balance = 300;

void withdraw(const string& msg, int amount) {
  int bal = bank_balance;
  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance = bal - amount;
}
```

Get balance

Compute the new balance

Save new balance

Making Concurrent Withdrawals

```
int main() {
  cout << "Starting balance is " << bank_balance << endl;

  thread bonnie(withdraw, "Bonnie", 100);
  thread clyde(withdraw, "Clyde", 100);

  bonnie.join();
  clyde.join();

  cout << "Final bank balance is " << bank_balance << endl;

  return 0;
}
```

Launch threads

Run withdraw function

Constructor

Wait for completion

Bonnie and Clyde Use ATMs

```
$ ./a.out
Starting balance is 300
Bonnie withdraws 100
Clyde withdraws 100
```

Is this correct?

What Happened?

Bonnie's thread, bal = 300

Clyde's thread, bal = 300

```
void withdraw(const string& msg, int amount) {
  int bal = bank_balance;
  string out_s = msg + " withdraws " + to_string(amt) + "\n";

  cout << out_s;
  bank_balance = bal - amount;
}
```

Context switch

```
void withdraw(const string& msg, int amount) {
  int bal = bank_balance;
  string out_s = msg + " withdraws " + to_string(amt) + "\n";

  cout << out_s;
  bank_balance = bal - amount;
}
```

Context switch

bal is still 300

bank_balance gets 200

bal is still 300

bank_balance gets 200

Profit!

What Happened: Race Condition

- Final answer depends on instructions from different threads are interleaved with each other
- Often occurs with shared writing of shared data
- Often due to read then update shared data
- What was true at the read is not true at the update

Critical Section Problem

```
int bank_balance = 300;

void withdraw(const string& msg, int amount) {
  int bal = bank_balance;
  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance = bal - amount;
}
```

We want to tell operating system not to run anything else here

When some thread is executing this ***critical section***, no other thread may execute it

The Critical-Section Problem

- n processes all competing to use some shared data
- Each process has a code segment, called critical section, in which the shared data is accessed.
- Problem – ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.
- What do we mean by “execute in its critical section”?

Solution to Critical-Section Problem

- ***Mutual Exclusion*** - If process Pi is executing in its critical section, then no other processes can be executing in their critical sections
- ***Progress*** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely
- ***Bounded Waiting*** - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
  - Assume that each process executes at a nonzero speed
  - No assumption concerning relative speed of the N processes

Critical Section Problem

```
int bank_balance = 300;

void withdraw(const string& msg, int amount) {
  int bal = bank_balance;
  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance = bal - amount;
}
```

This is a ***critical section***

Let's just think about mutual exclusion for now

Critical Section Problem

```
bool lock = false;

int bank_balance = 300;

void withdraw(const string& msg, int amount) {
  while (lock == true)
    ;
  lock = true;

  int bal = bank_balance;
  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance = bal - amount;

  lock = false;
}
```

Test if another thread is holding the lock

Take the lock

Spin if it is

Fall through when lock == false

Execute critical section

Release lock

Aside

```
bool lock = false;

int bank_balance = 300;

void withdraw(const string& msg, int amount) {

  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance -= amount;

}
```

Still a race

Aside

```
bool lock = false;

int bank_balance = 300;

void withdraw(const string& msg, int amount) {

  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;
  bank_balance = bank_balance - amount;

}
```

Then write

Still a race

Read

Compute

Critical Section Problem

Critical section

```
bool lock = false;

int bank_balance = 300;

void withdraw(const string& msg, int amount) {

  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;


  bank_balance = bank_balance - amount;

}
```

Solution (?)

```
bool lock = false;

int bank_balance = 300;

void withdraw(const string& msg, int amount) {

  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;

  while (lock == true)
    ;
  lock = true;

  bank_balance = bank_balance - amount;

  lock = false;
}
```

Test if another thread is holding the lock

Take the lock

Spin if it is

Execute critical section

Fall through when lock == false

Release lock

Solution (?)

Common pattern (when correct)

Test if another thread is holding the lock

```
bool lock = false;

int bank_balance = 300;

void withdraw(const string& msg, int amount) {

  string out_string = msg + " withdraws " + to_string(amount) + "\n";
  cout << out_string;

  while (lock == true)
    ;
  lock = true;

  bank_balance = bank_balance - amount;

  lock = false;
}
```

Take the lock

Spin if it is

Lock might be taken between the test and the set

Fall through when lock == false

We've traded one critical section problem for another

Synchronization Hardware

- Many systems provide hardware support for critical section code
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- Modern machines provide special ***atomic*** hardware instructions
    - Atomic = non-interruptable
  - Either test memory word and set value
  - Or swap contents of two memory words

Test and Set

```
bool TestAndSet (bool& target)
{
  bool rv = target;
  target = TRUE;
  return rv:
}
```

```
bool TestAndSet (bool *target)
{
  bool rv = *target;
  *target = TRUE;
  return rv:
}
```

These are the semantics, not the implementation

Implemented in hardware as an invisible instruction

Compare And Swap

```
void CompareAndSwap (bool& a, bool& b)
{
  bool temp = a;
  a = b;
  b = temp:
}
```

```
void CompareAndSwap (bool *a, bool *b)
{
  bool temp = *a;
  *a = *b;
  *b = temp:
}
```

These are the semantics, not the implementation

Implemented in hardware as an invisible instruction

Correct Withdraw

```
int bank_balance = 300;
bool lock = false;

void withdraw(const string& msg, int amount) {
  string out_s = msg + " withdraws " + to_string(amt) + "\n";
  cout << out_s;

  while (TestAndSet(lock) == true)
    ;

  bank_balance -= amount;

  lock = false;
}
```

Under what condition will we fall through?

What is the state of the lock?

Spin while the value is true (another thread holds the lock)

Release the lock

Correct Withdraw

```
int bank_balance = 300;
bool lock = false;

void withdraw(const string& msg, int amount) {
  string out_s = msg + " withdraws " + to_string(amt) + "\n";
  cout << out_s;

  while (TestAndSet(lock) == true)
    ;

  bank_balance -= amount;

  lock = false;
}
```

What is the CPU doing?

How is it affecting other threads?

”Spin lock” (common pattern)

Is this a good programming abstraction?

Multitasking on Multicore

Nonetheless, this is the essence of ***parallel*** computing

Parallel computation isn't done until all cores are done

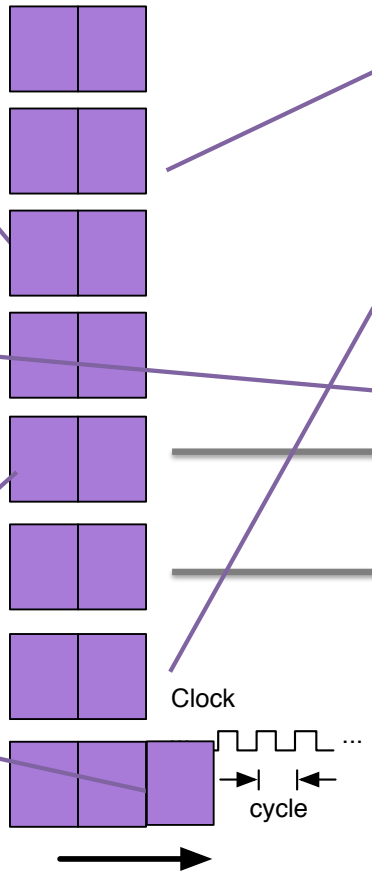
Not the same as concurrent

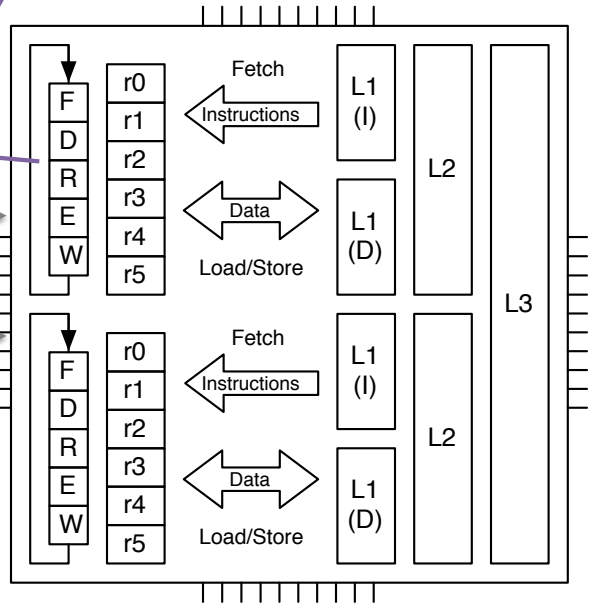
In 1/8 the time (?)

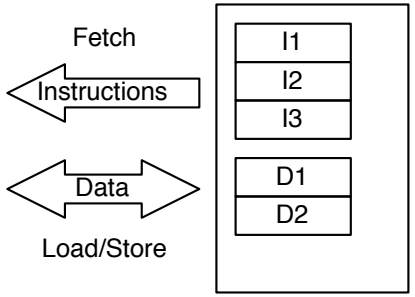
Need enough cores (8)

Work needs to be balanced

oops







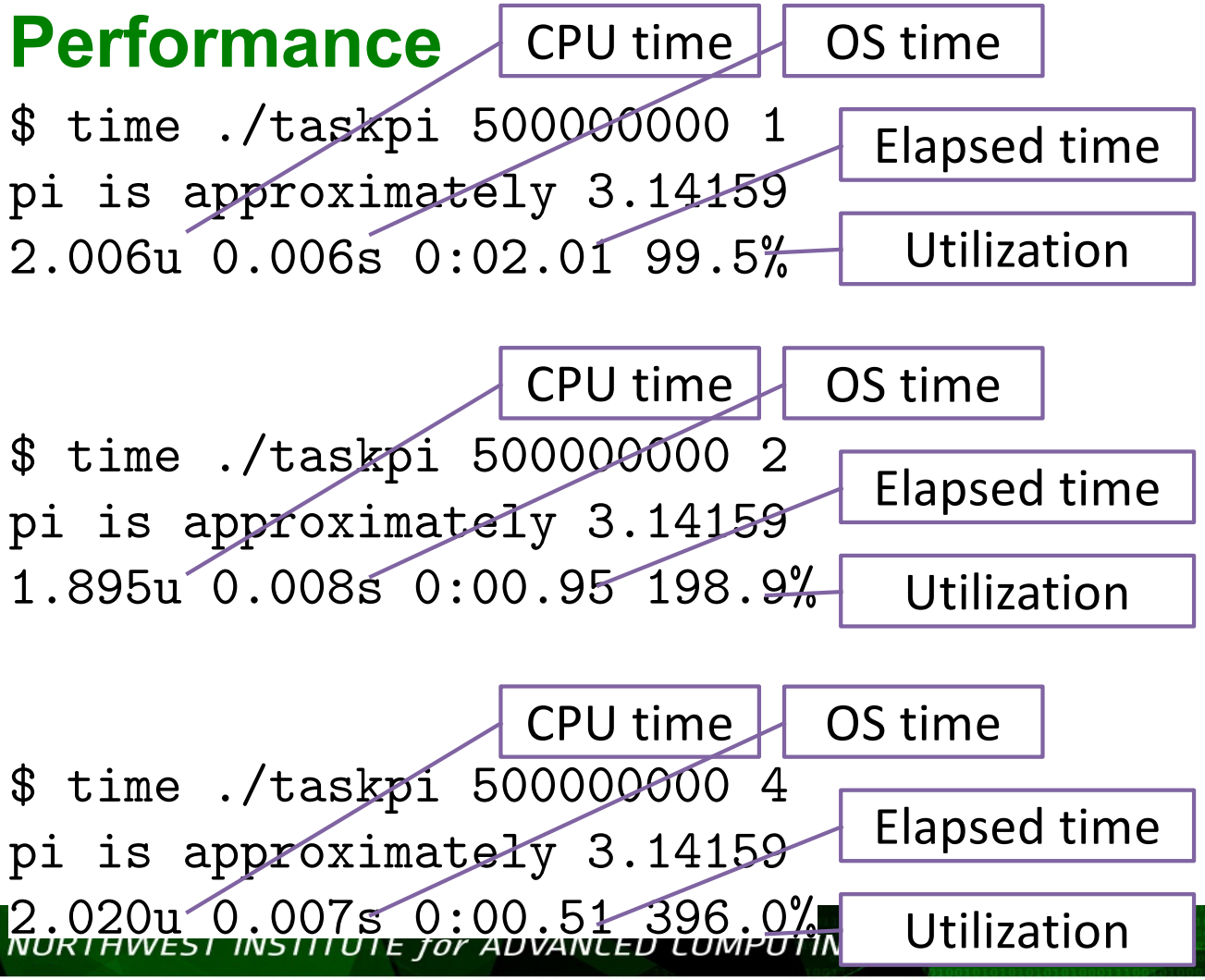
Numerical Quadrature Task

```
double partial_pi(unsigned long begin, unsigned long end, double h) {
  double partial_pi = 0.0;
  for (unsigned long i = begin; i < end; ++i) {
    partial_pi += 4.0 / (1.0 + (i*h*i*h));
  }
  return partial_pi;
}
```

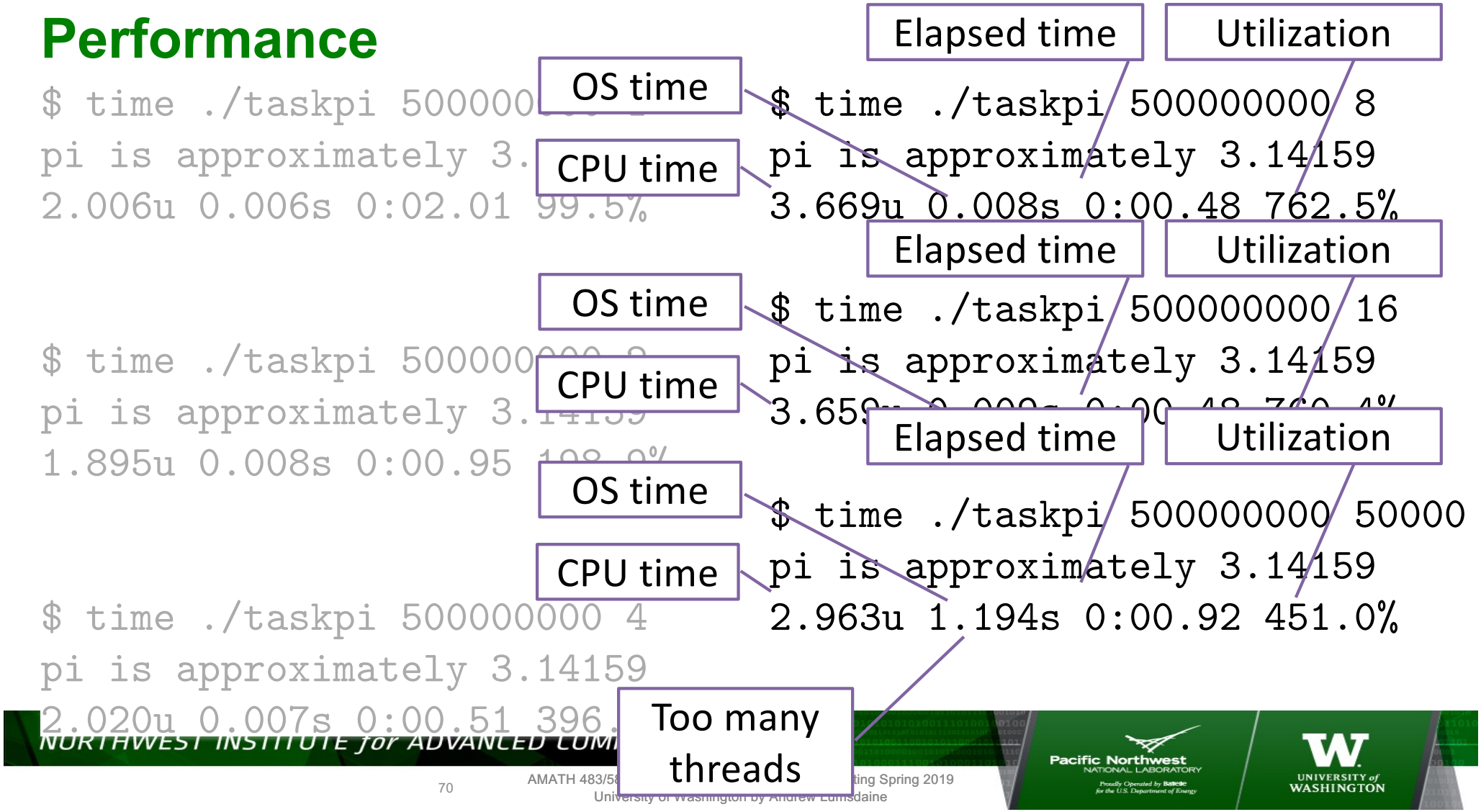
Nothing remarkable about this function

Nothing remarkable about this function

Performance



Performance



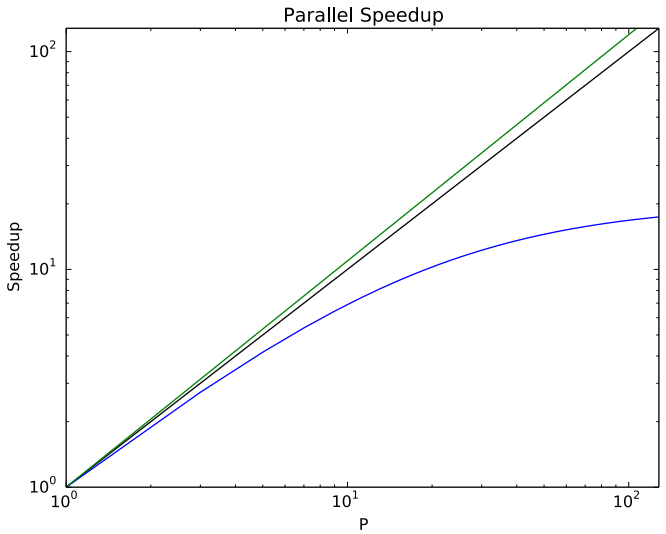
Parallel Speedup, Parallel Efficiency

Speedup on p processing units

Time to run problem size n on one PU

Time to run problem size n on p PUs

$$S(p) = \frac{T(n,1)}{T(n,p)}$$



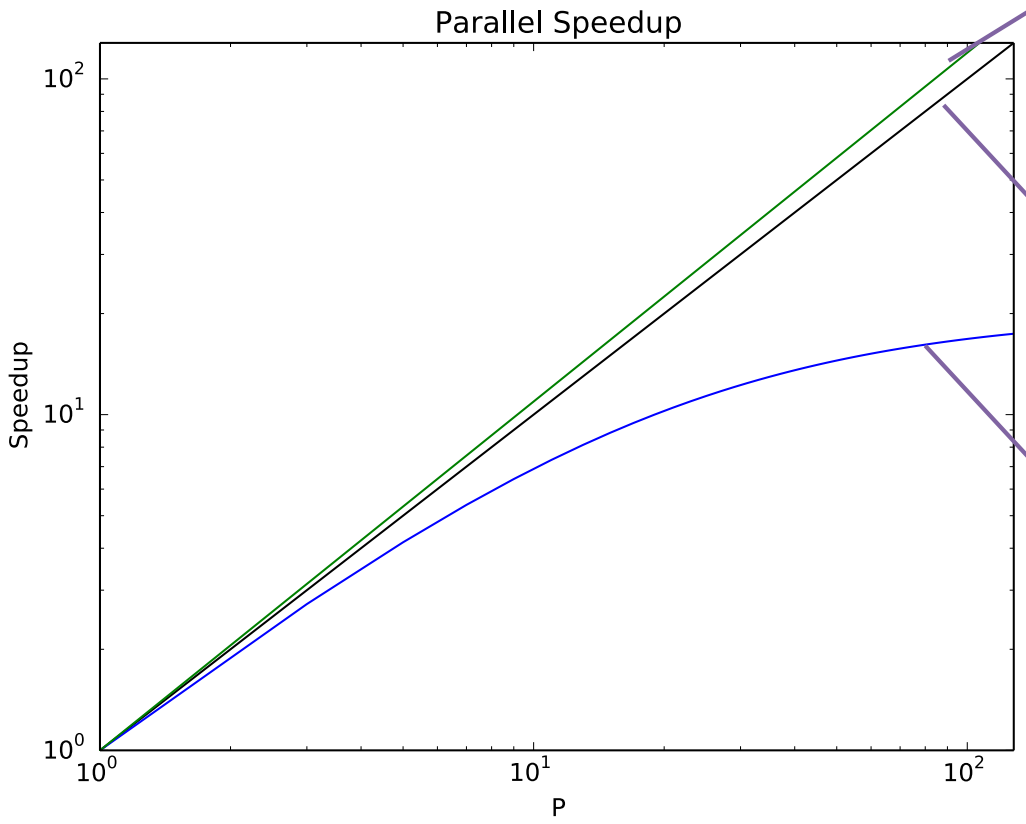
Efficiency on p processing units

Ideal parallel execution time

Divided by actual parallel execution time

$$E(p) = \frac{T(n,1)/p}{T(n,p)} = \frac{T(n,1)/T(n,p)}{p} = \frac{S(p)}{p}$$

Scaling

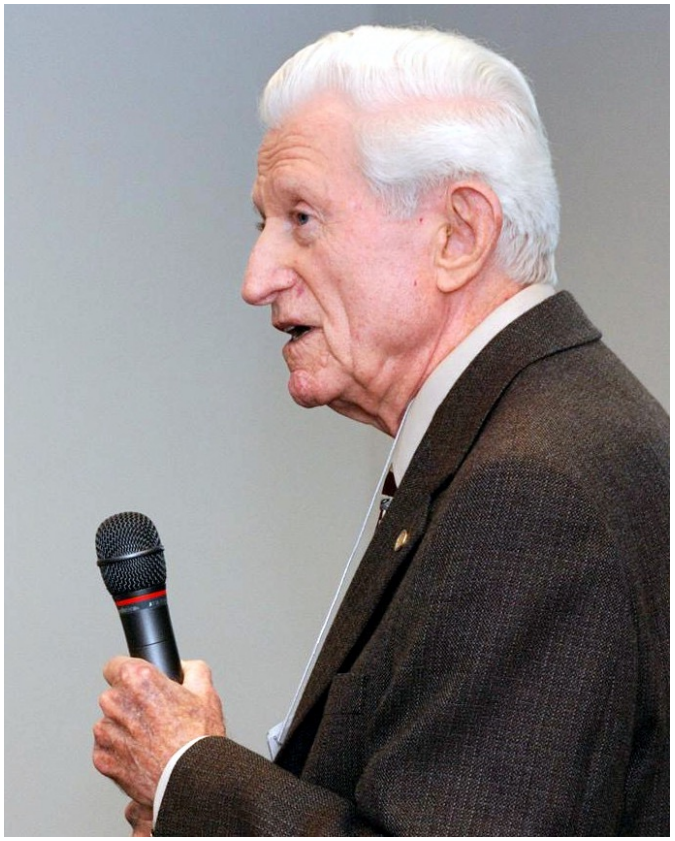


Superlinear (fishy)

Linear (ideal)

Sublinear (typical)

Name This Famous Person

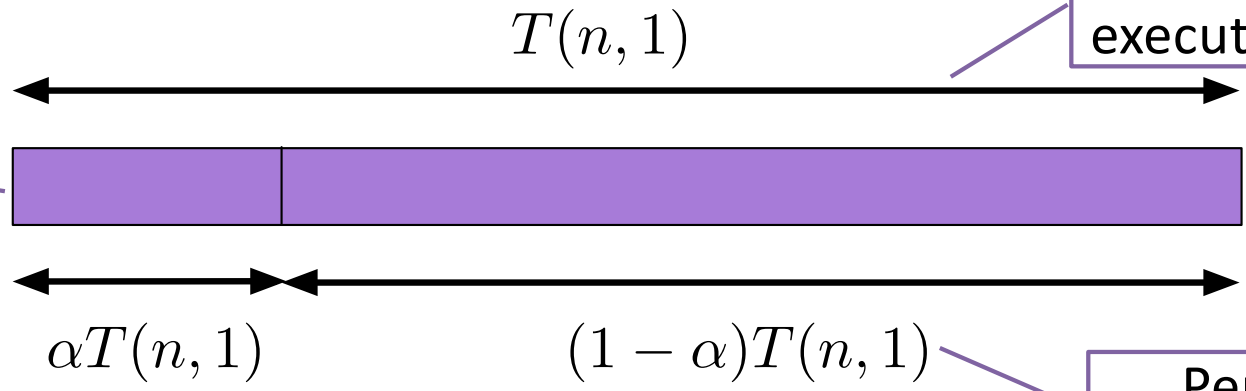


"Validity of the single processor approach to achieving large-scale computing capabilities," AFIPS Conference Proceedings (30): 483–485, 1967.

Gene Amdahl (1922-2015)

Amdahl's Law

Limits to Parallelism (Amdahls's Law)



Sequential execution time

Inherently sequential

Inherently sequential

Perfectly parallelizable

$$T(n,1) = \alpha T(n,1) + (1-\alpha)T(n,1)$$

Perfectly parallelizable

$$\begin{aligned} T(n,p) &= \alpha T(n,1) + \tfrac{1}{p}(1-\alpha)T(n,1) \\ &= T(n,1)(\alpha + \tfrac{1}{p}(1-\alpha)) \end{aligned}$$

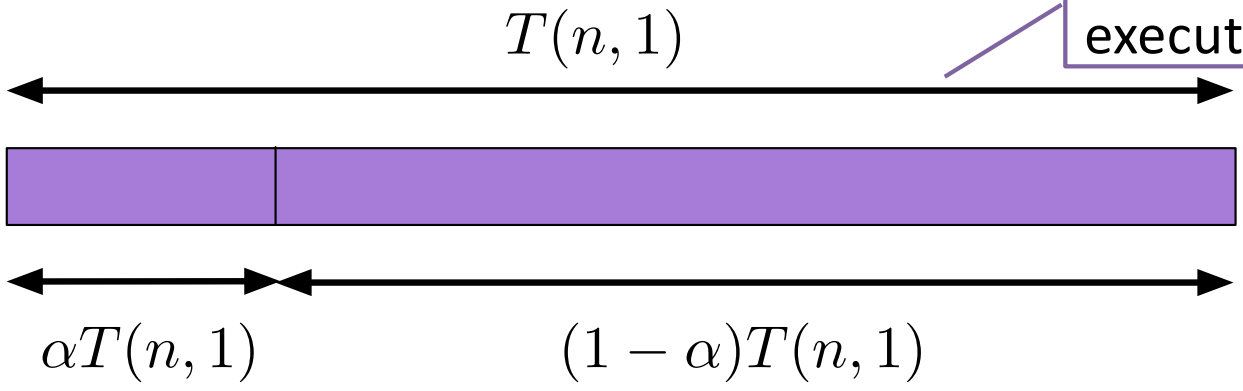
Ideal speedup (for parallelizable portion)

Sequential portion

Limits to Parallelism (Amdahls's Law)

Sequential execution time

Inherently sequential



Speedup

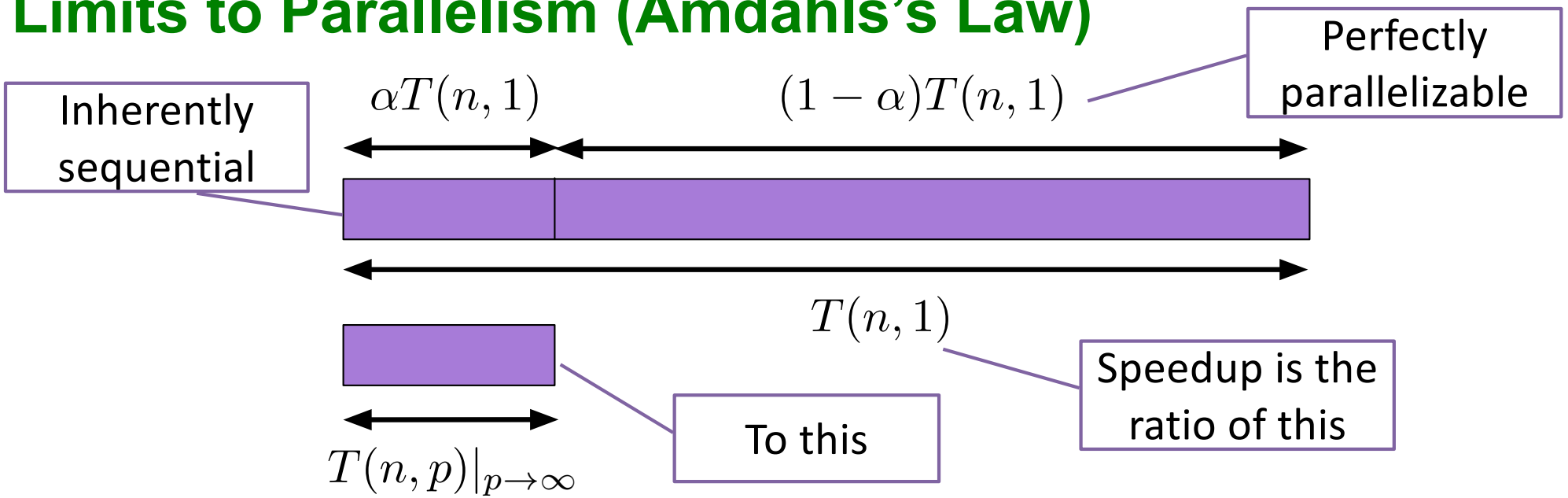
Perfectly parallelizable

$$S(p) = \frac{T(n,1)}{T(n,p)} = \frac{T(n,1)}{T(n,1)[\alpha + \frac{1}{p}(1-\alpha)]}$$

$$= \frac{1}{\alpha + \frac{1}{p}(1-\alpha)} \leq \frac{1}{\alpha}$$

$$\lim_{p\to\infty} S(p) = \frac{1}{\alpha}$$

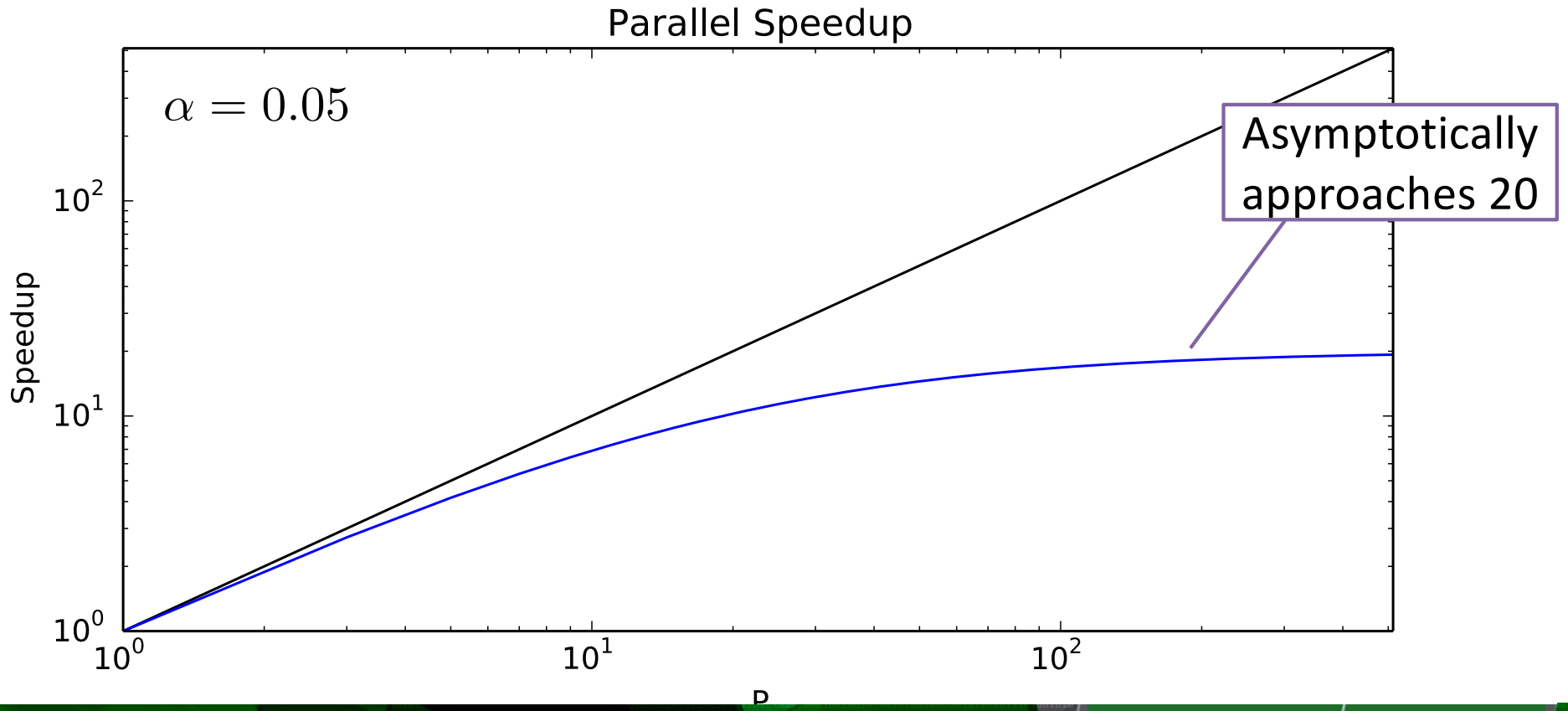
Limits to Parallelism (Amdahls's Law)



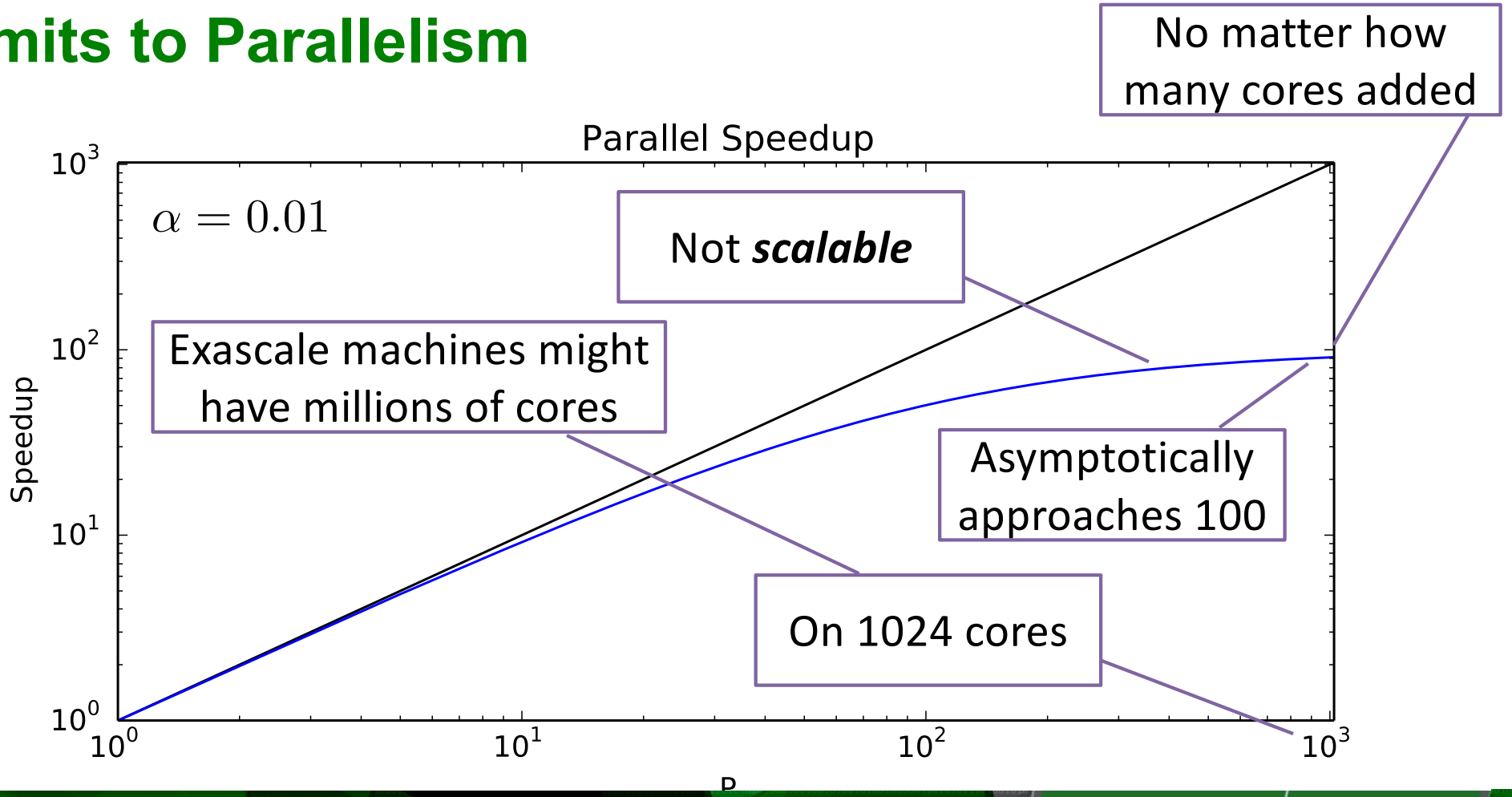
$$\lim_{p\to\infty} S(p) = \frac{1}{\alpha}$$

$$S(p) = \frac{T(n,1)}{T(n,p)}$$

Limits to Parallelism (Amdahl's Law)

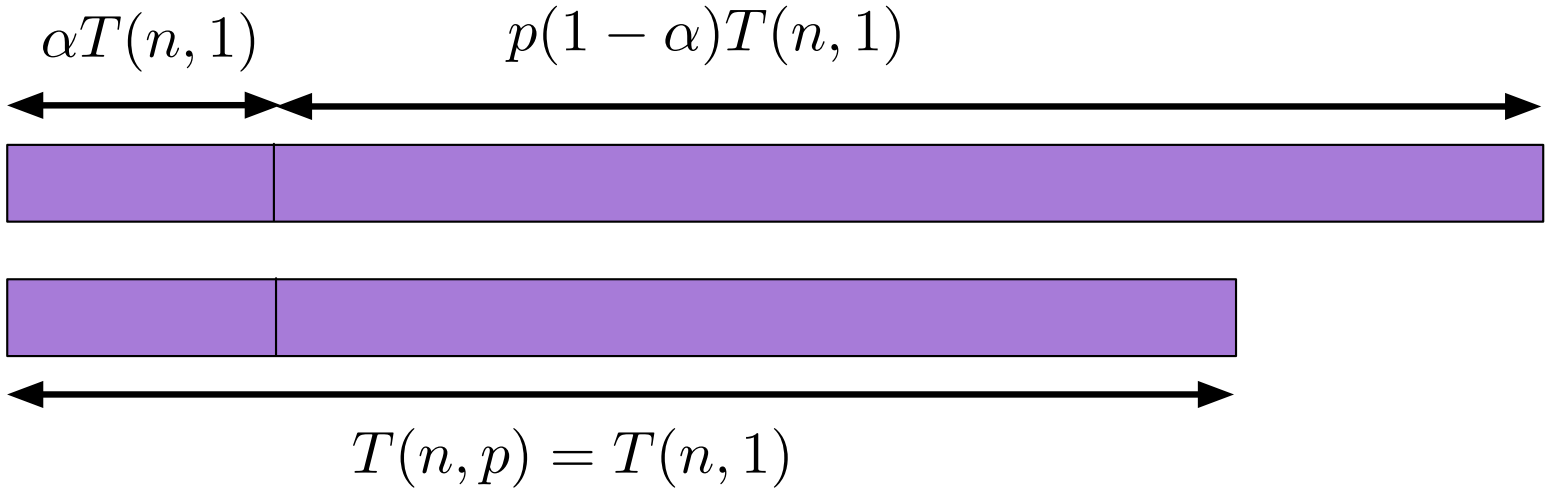


Limits to Parallelism

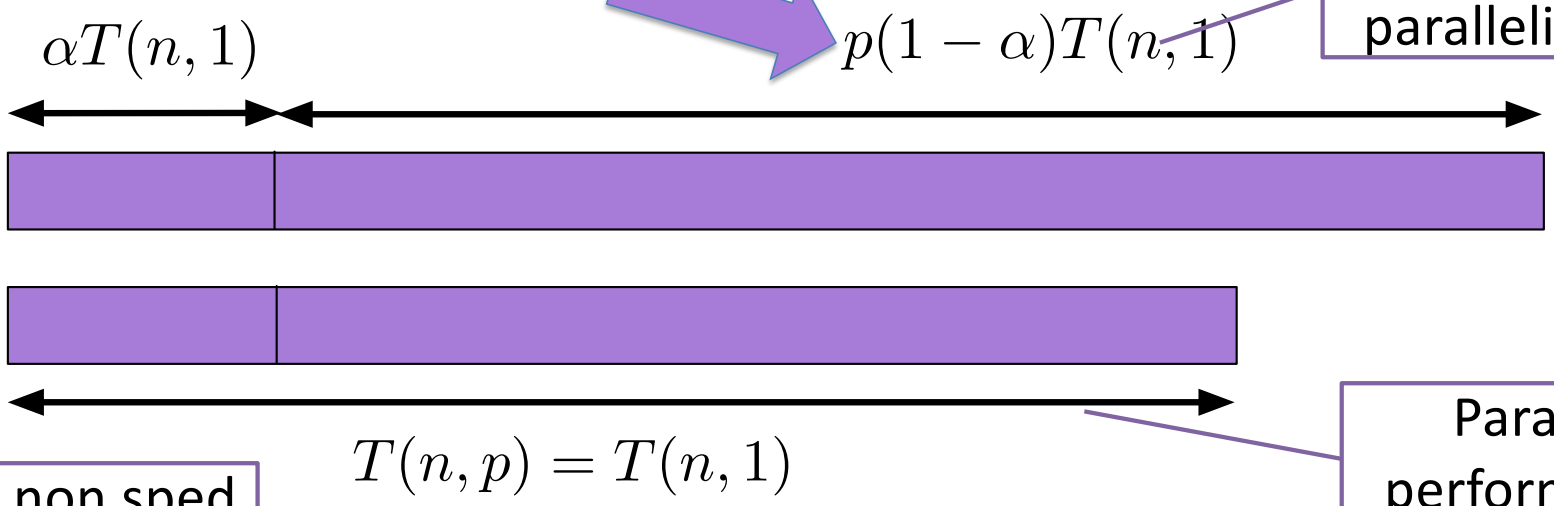


There are no Limits (Gustafson's Law)

- Doing the same problem faster and faster is not how we use parallel computers
- Rather, we solve bigger and more difficult problems
- I.e., the amount of parallelizable work grows



There are no Limits (Gustafson's Law)



Perfectly parallelizable

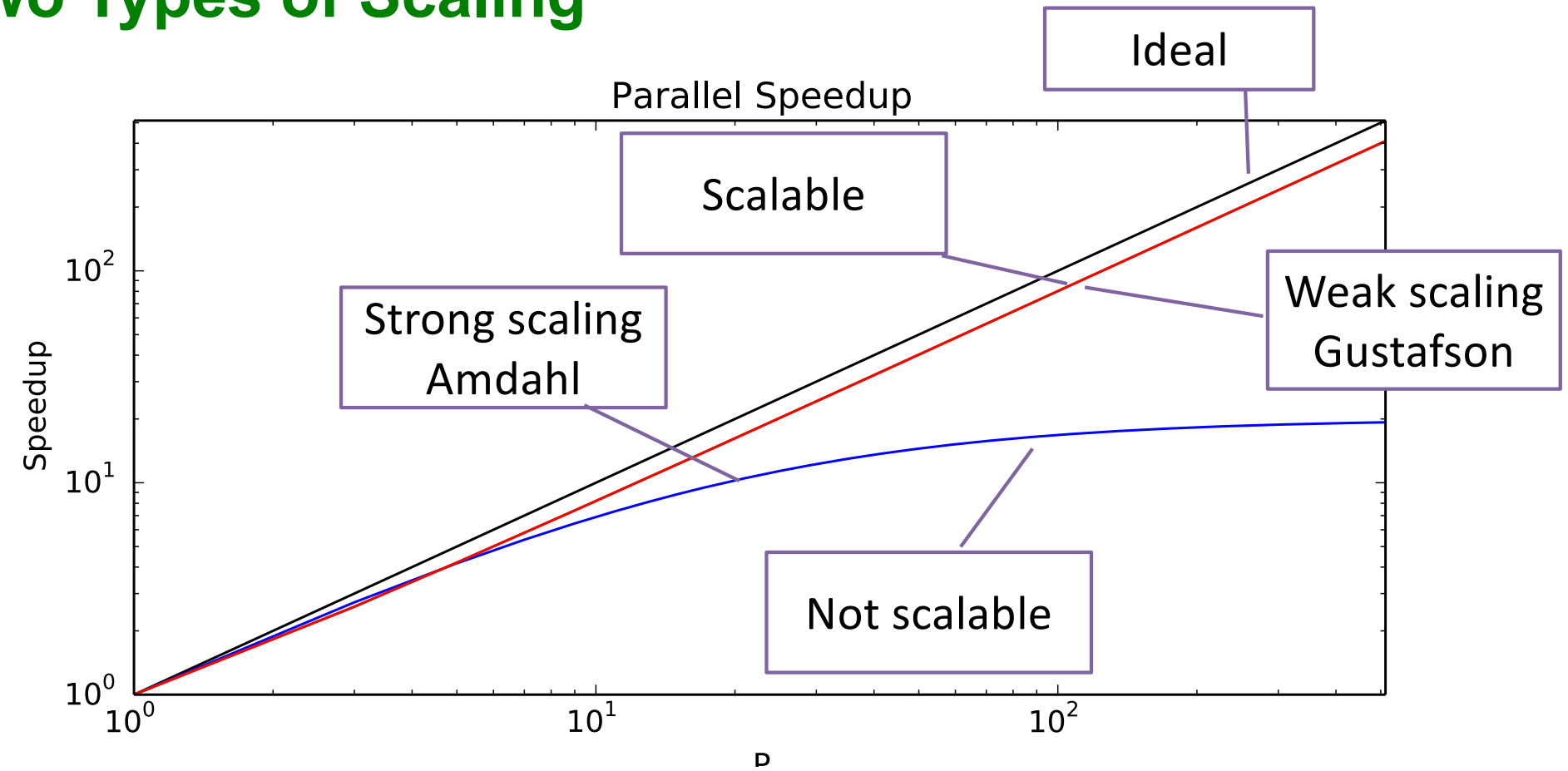
Parallel performance

Ratio of non sped up to sped up

$$S(p) = \frac{\alpha T(n,1)+p(1-\alpha)T(n,1)}{T(n,p)} = \frac{\alpha T(n,1)+p(1-\alpha)T(n,1)}{T(n,1)} = \alpha + p(1-\alpha)$$

$$E(p) = \frac{S(p)}{p} \quad \Rightarrow \quad \lim_{p\to\infty} E(p) = (1-\alpha)$$

Two Types of Scaling



Stay Tuned

- C++ threads
- C++ async()
- C++ atomics

Thank you!

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