Software Performance Engineering

Lecture 6
Multicore Programming

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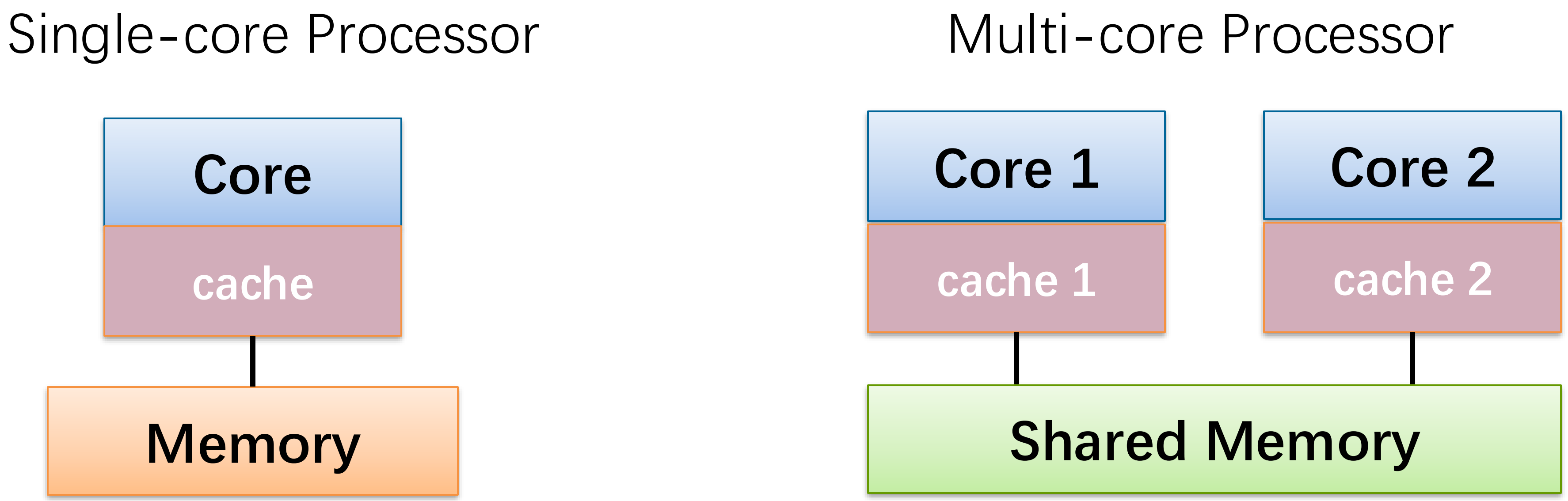
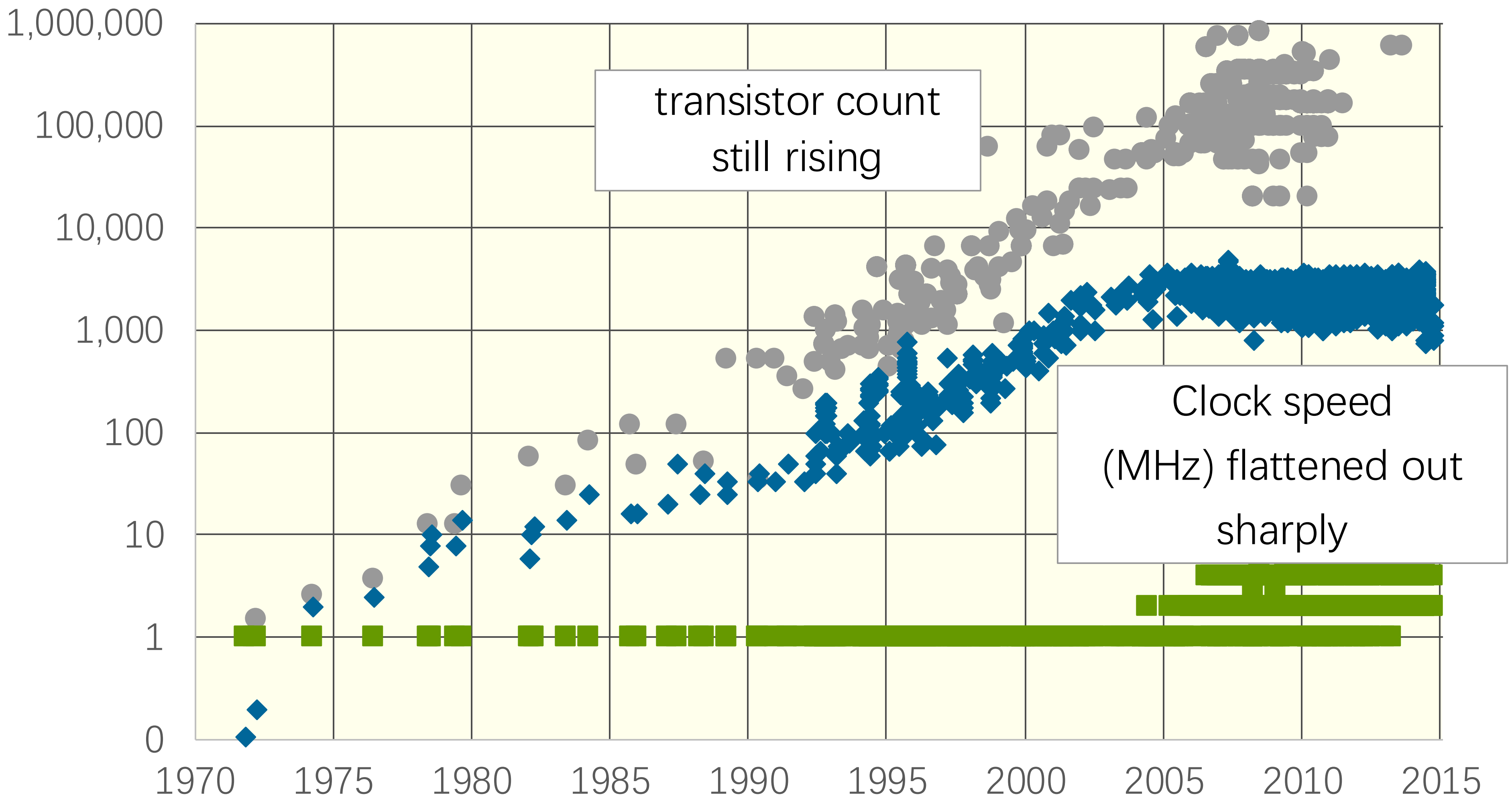
From Single-Core to Multi-Core

- **Why Multicore?** **Performance!**



Moore's Law



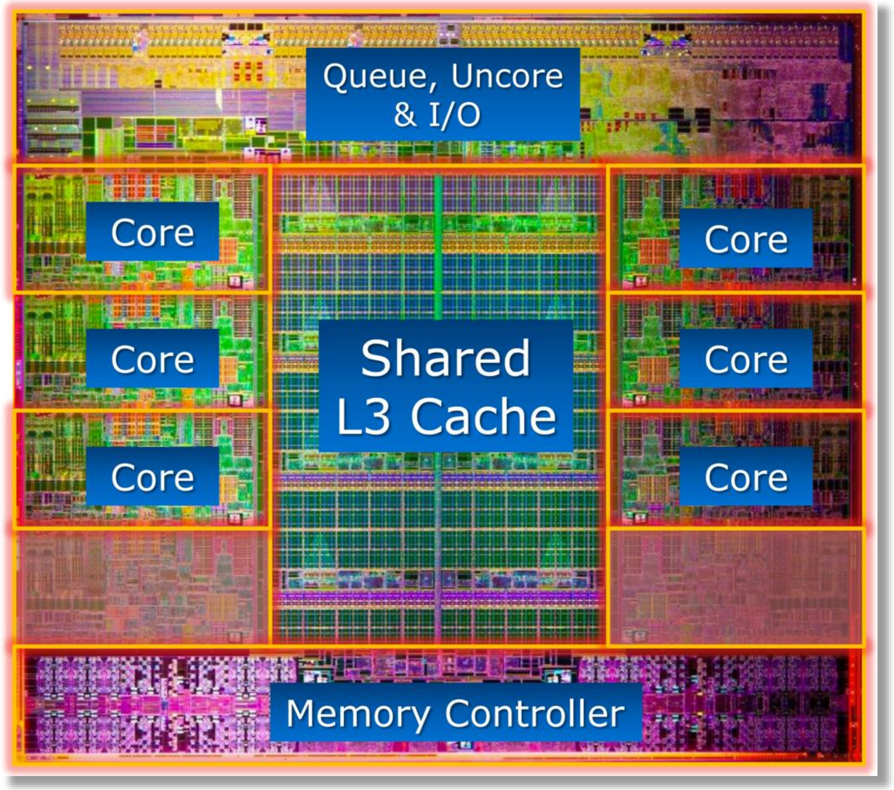
Processor data from Stanford's CPU DB [DKM12].

Power Wall at 4 GHz

- Power $\approx$ Voltage^2 $*$ Frequency
- The end of Dennard Scaling

Vendor Solution: Multicore

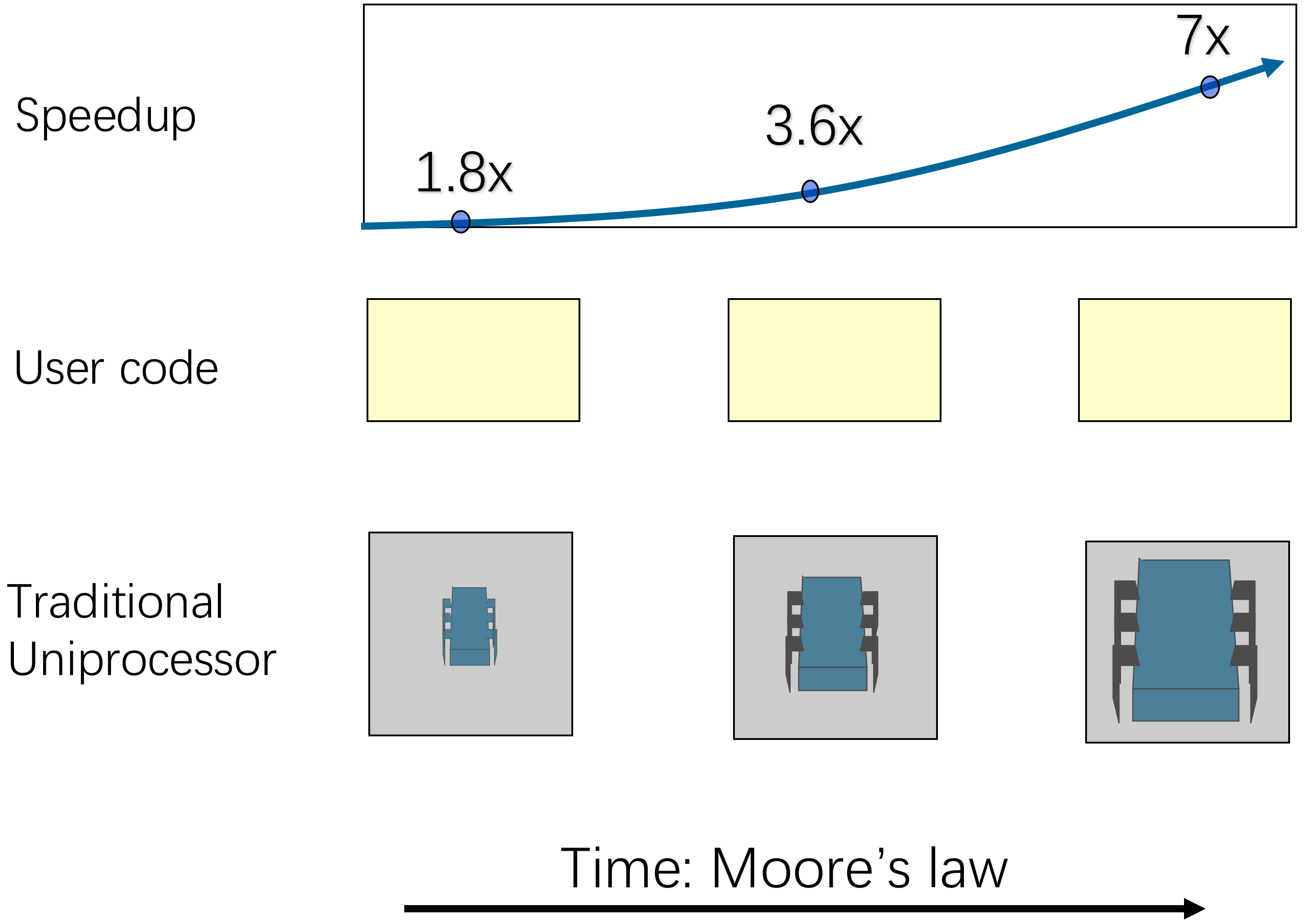
- To scale performance, vendors put many processing cores on the chip
- Each generation of Moore's Law potentially doubles the number of cores



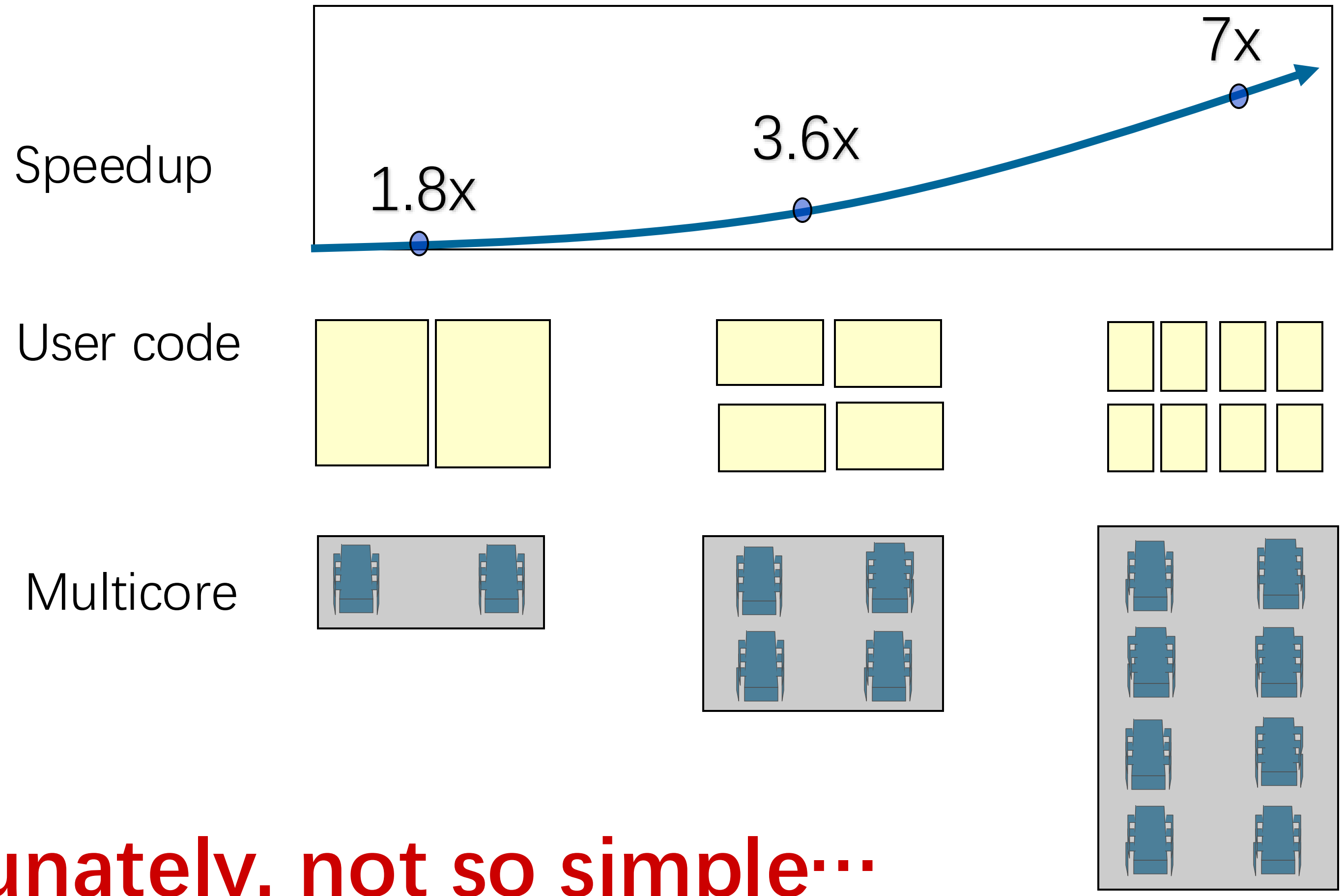
Intel Core i7 3960X
(Sandy Bridge E), 2011

- 6 cores
- 3.3 GHz
- 15-MB L3 cache

Historical Software Scaling



Ideal Multicore Scaling



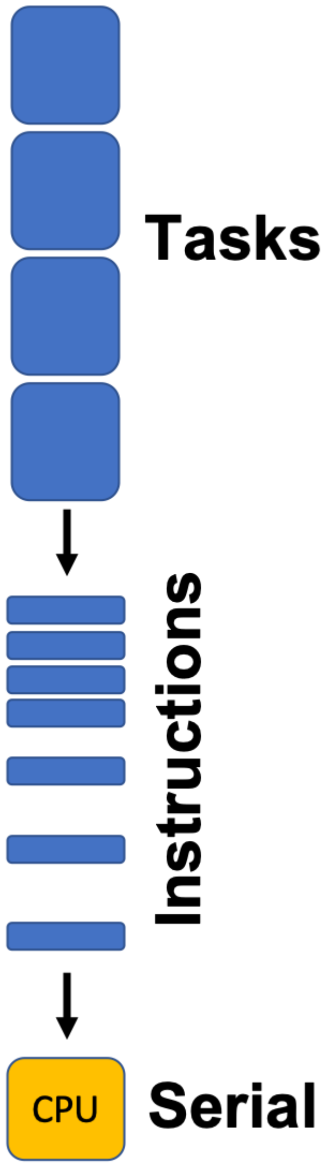
Unfortunately, not so simple…

Free Lunch is Over *

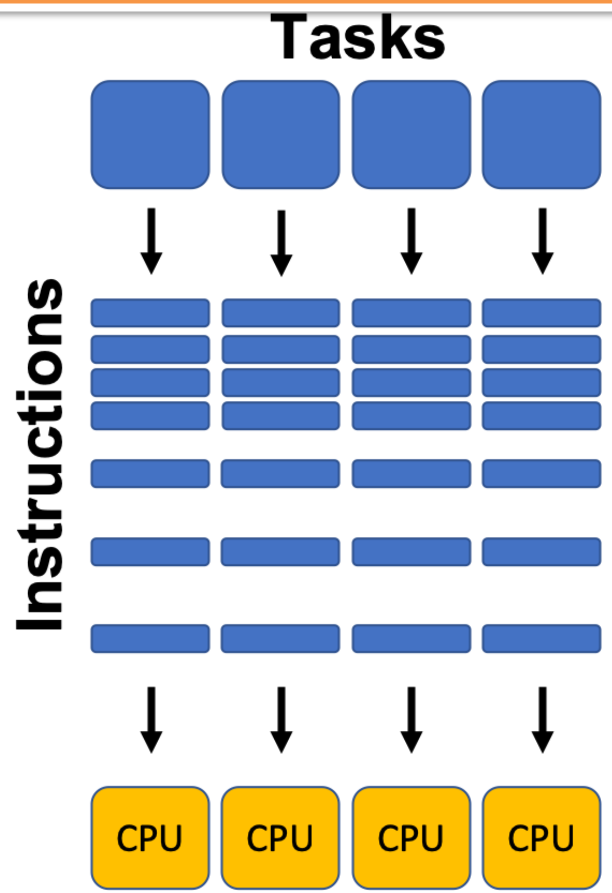
* Herb Sutter, The Free Lunch Is Over: A Fundamental Turn Toward Concurrency in Software, 2010

Serial vs. Parallel Programming

Parallel programming is hard!



Serial computing



Parallel computing

Load Imbalance

time

Task T1

Task T2

Task T3

Task T4

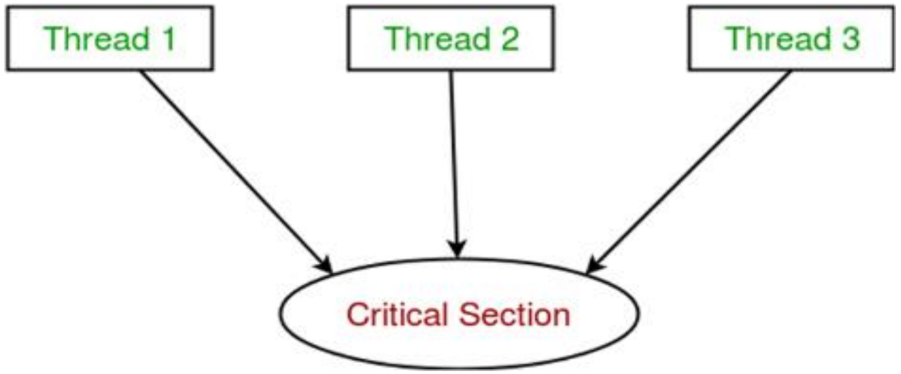
Task T5

Serial program

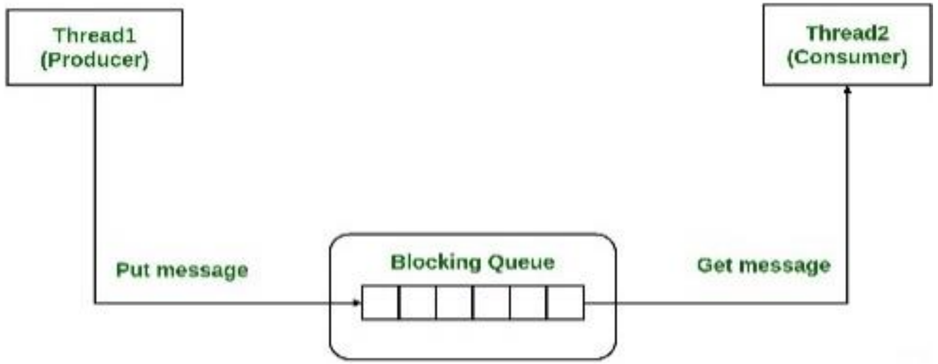
Task T1 Task T2 Task T3 Task T4 Task T5

Parallel program

Synchronization & Communication



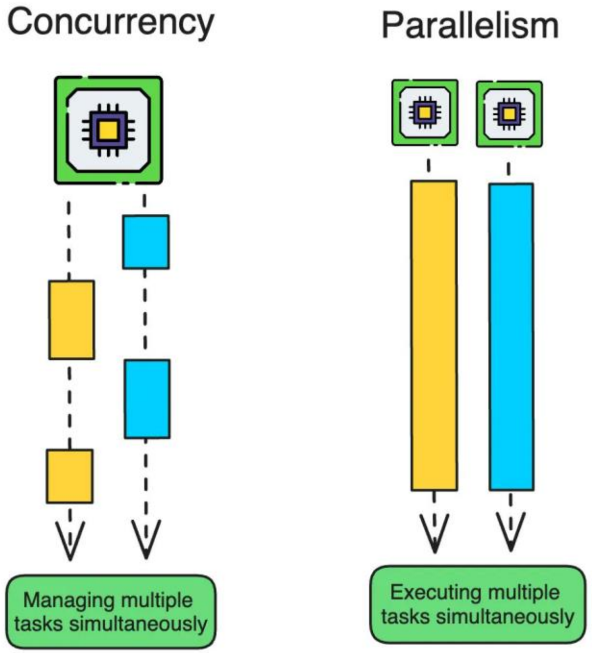
- Synchronization



- Communication

Concurrency vs. Parallelism

- A **parallel** program uses multiple CPU cores, each core performing a task independently.
- **Concurrency** enables a program to deal with multiple tasks even on a single CPU core
  - The core switches between tasks (i.e. threads) without necessarily completing each one → time sharing
- A program can have both, neither or a combination of parallelism and concurrency characteristics.

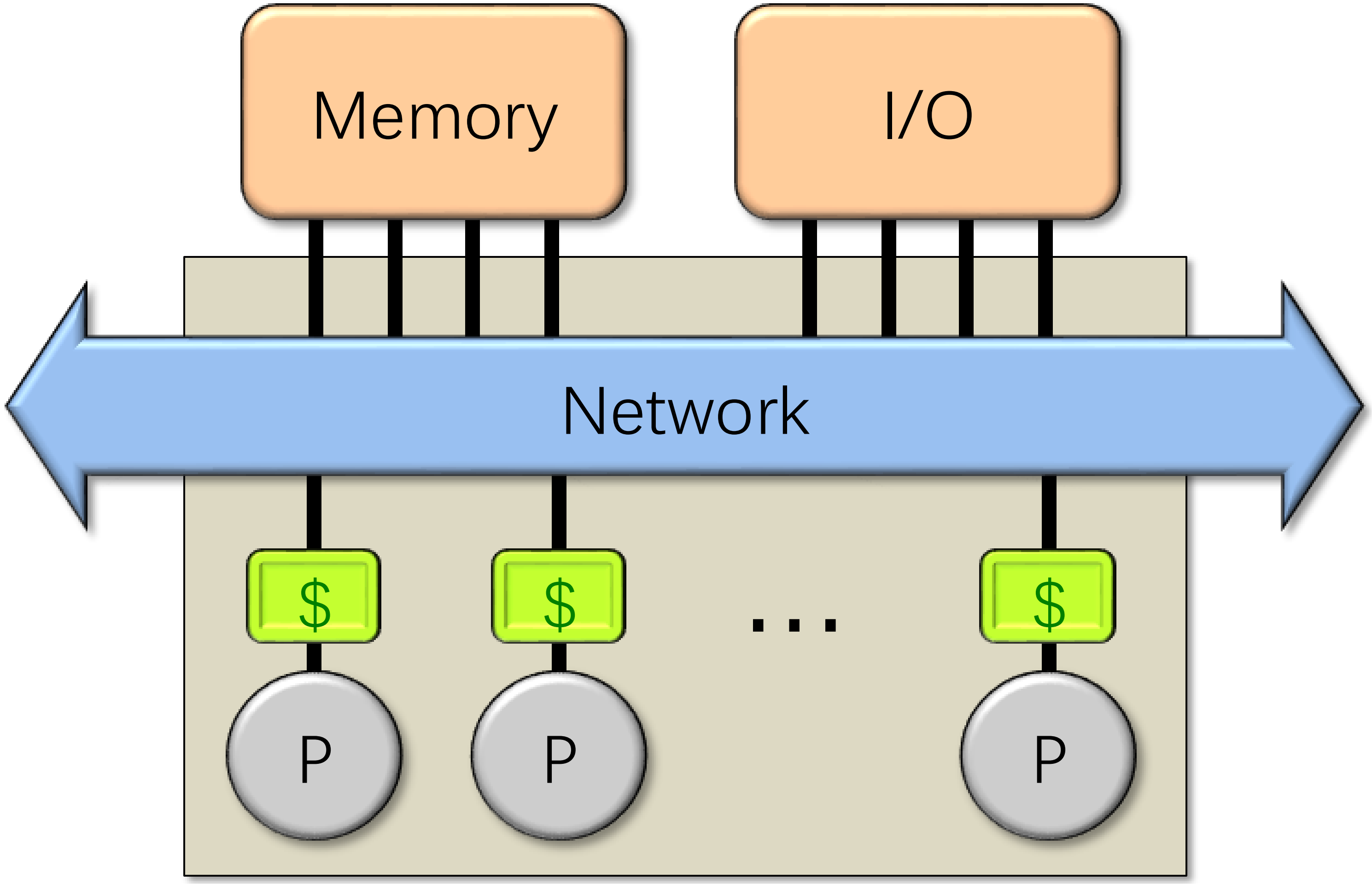


OUTLINE

- Shared-Memory Hardware
- How to **Program** Shared-Memory Hardware
  - Pthreads (and WinAPI Threads)
  - Threading Building Blocks (TBB)
  - OpenMP
  - Cilk

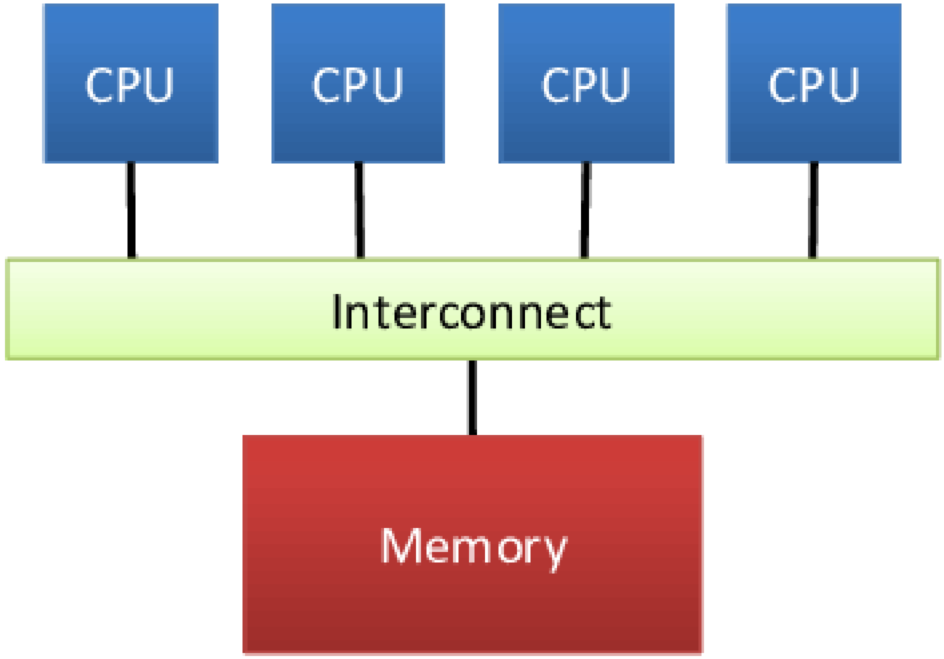
Shared-Memory Hardware

Abstract Multicore Architecture

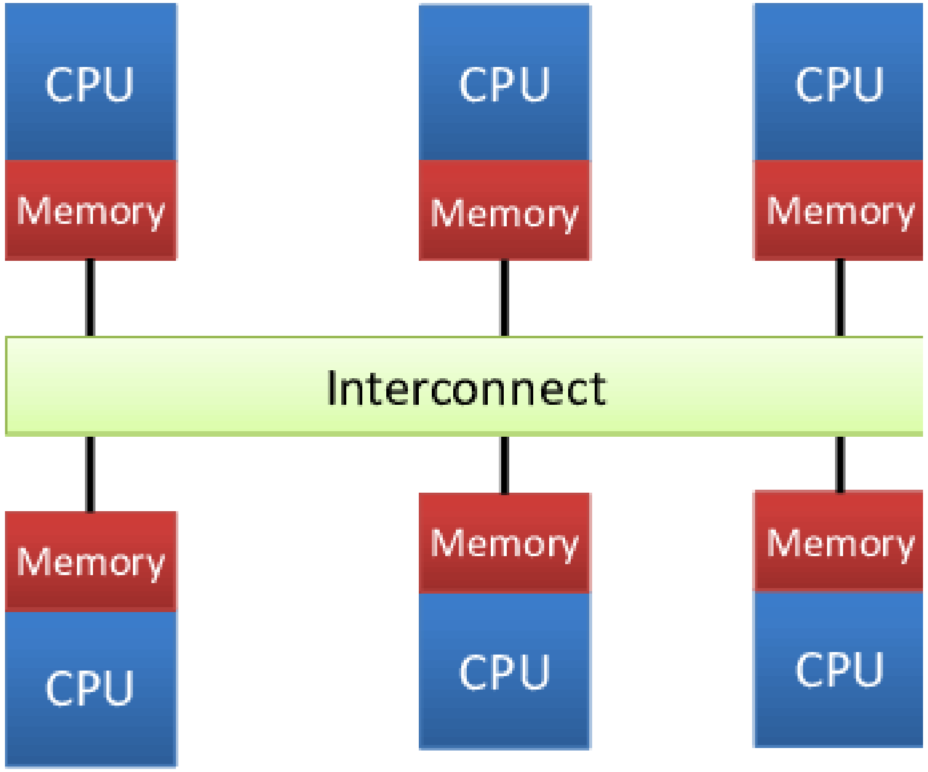


Shared Memory vs. Distributed Memory

Shared Memory

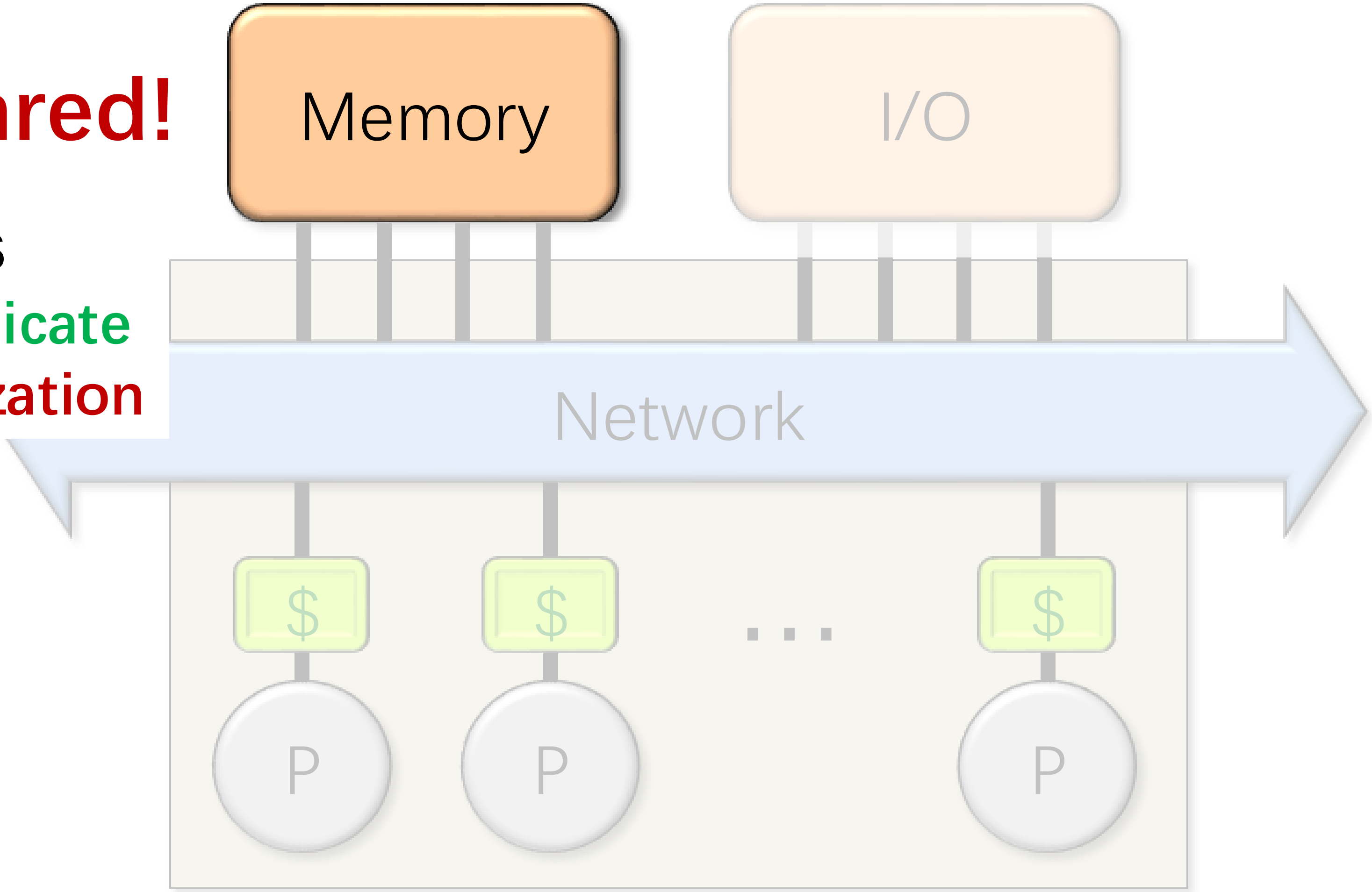


Distributed Memory



Abstract Multicore Architecture

Shared!

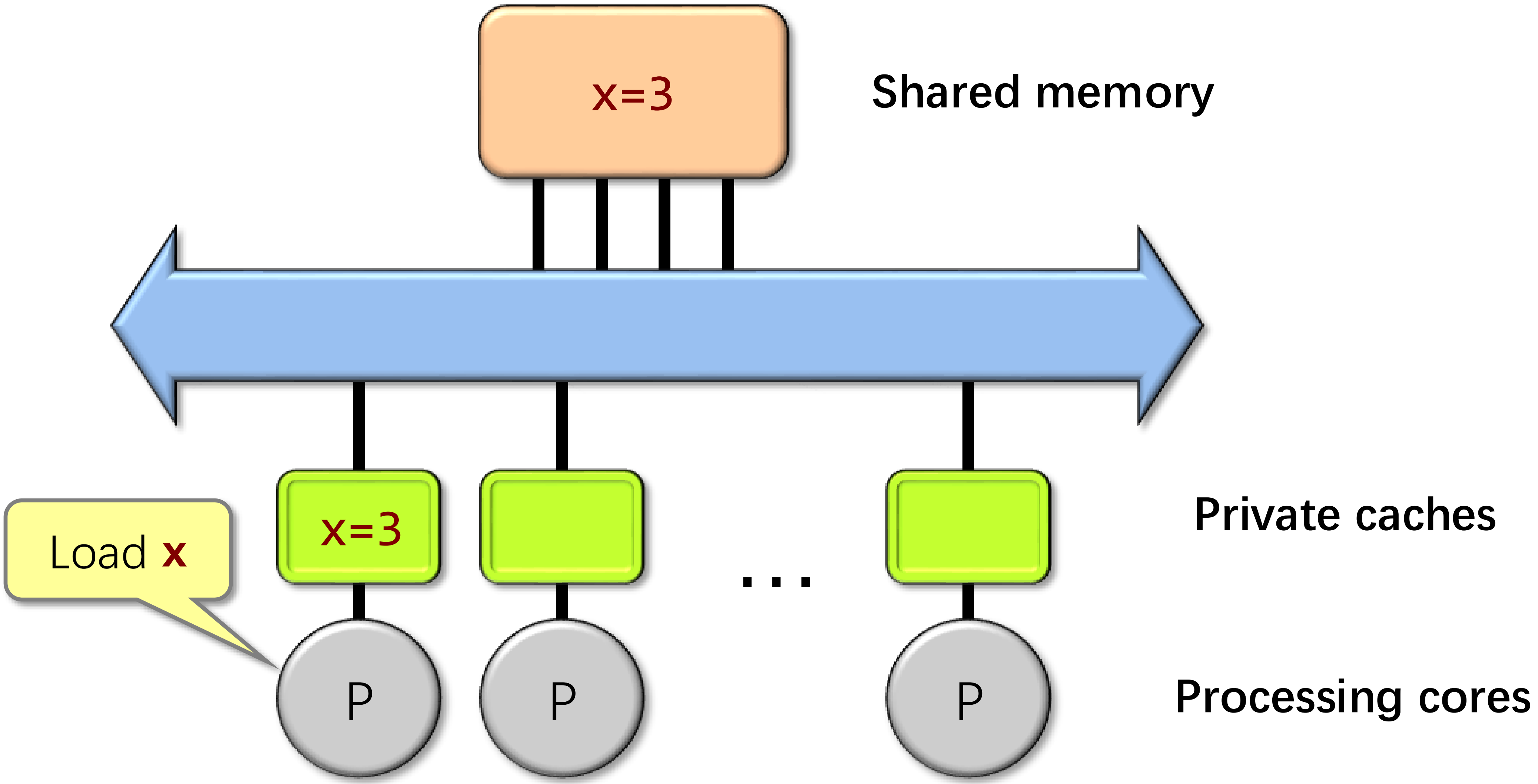


Pros and Cons

Easy to communicate

Need synchronization

Cache Coherence



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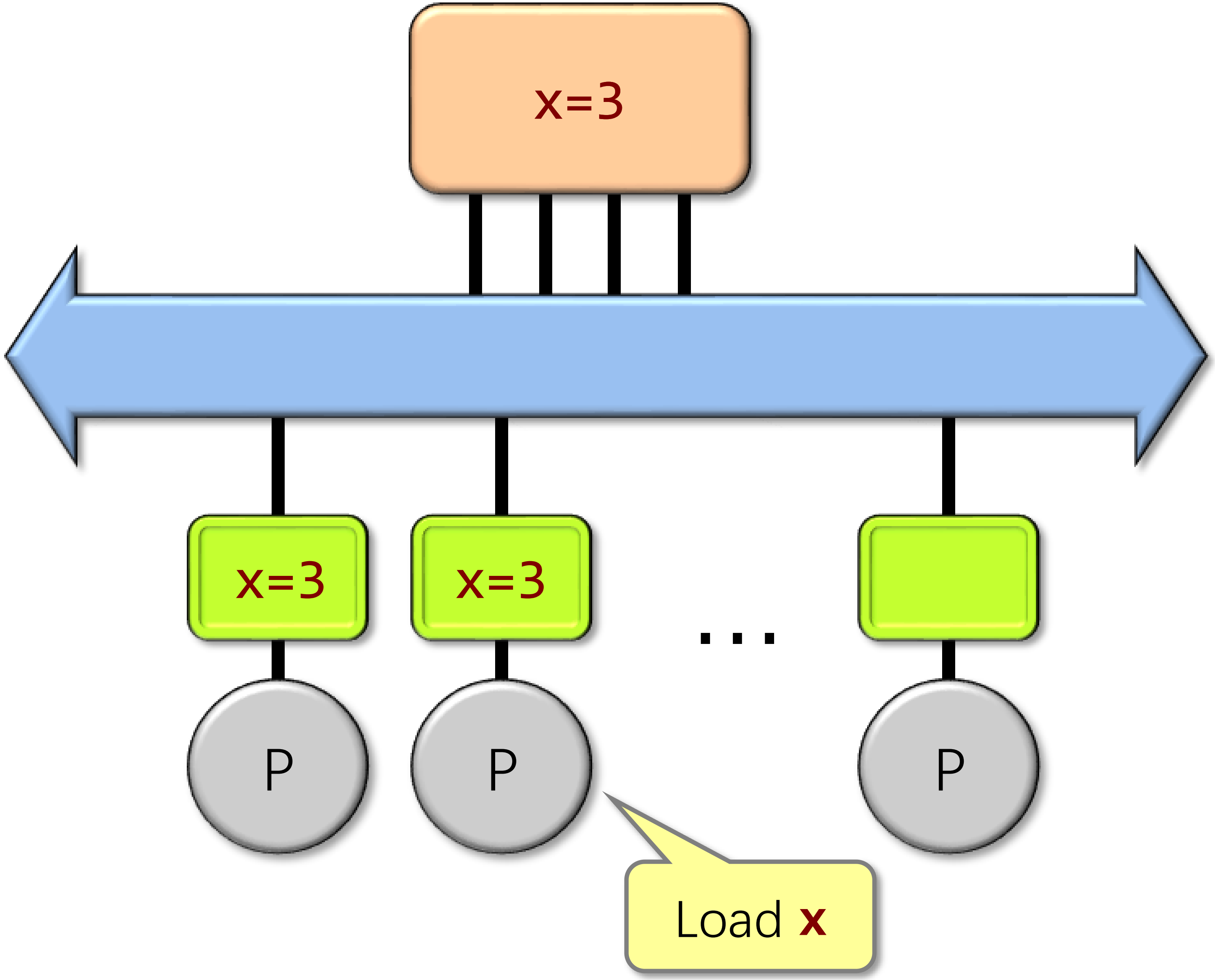

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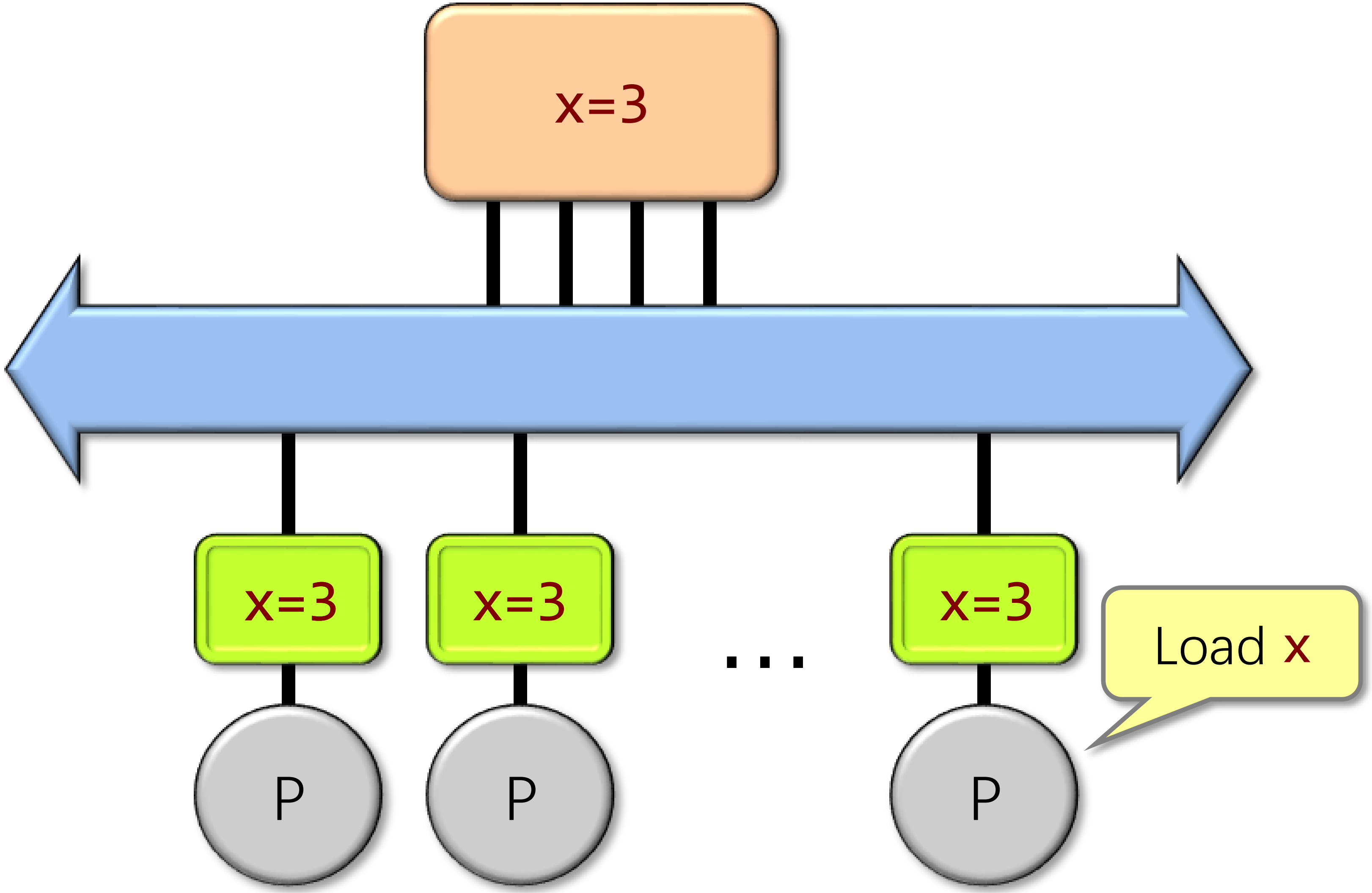

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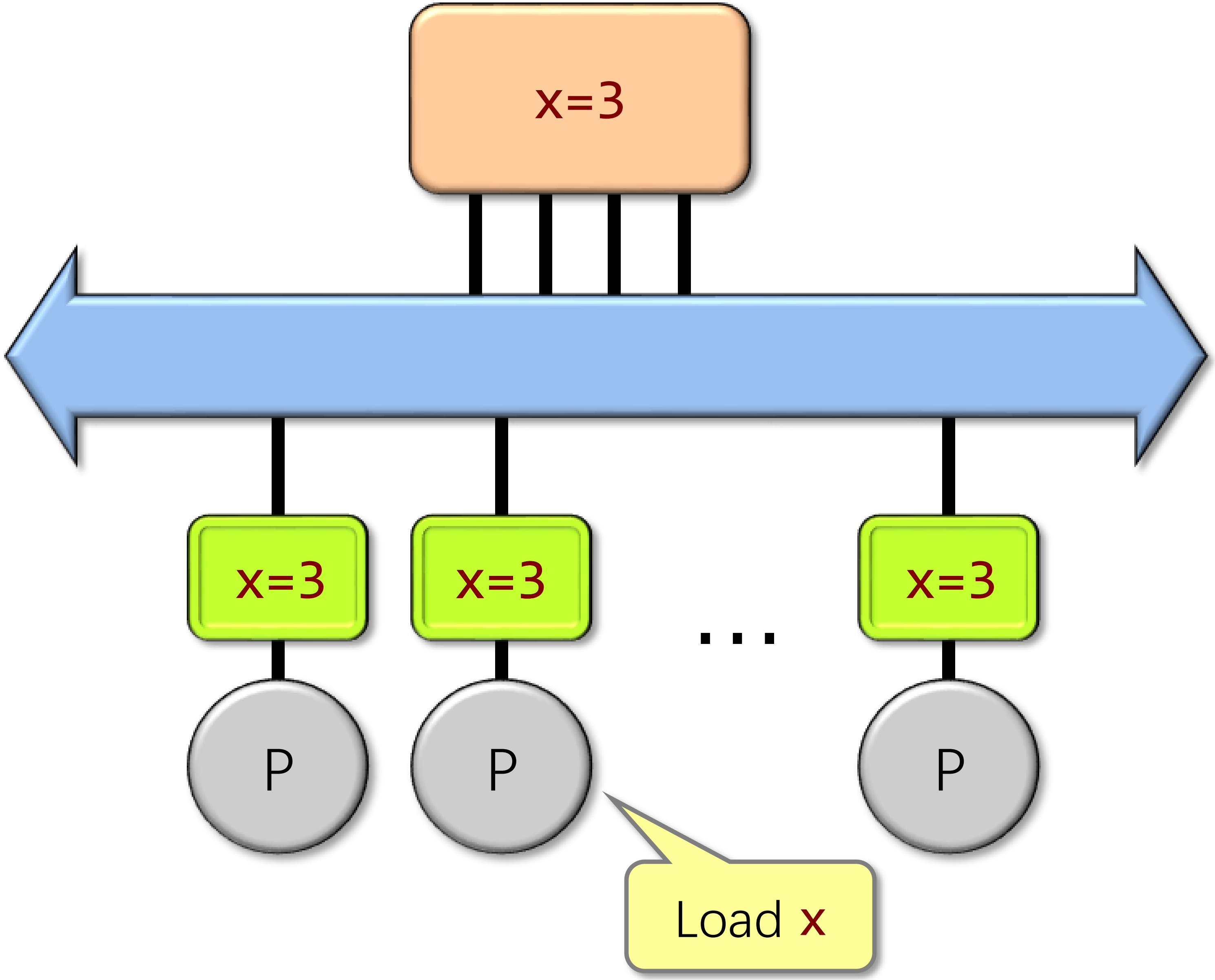

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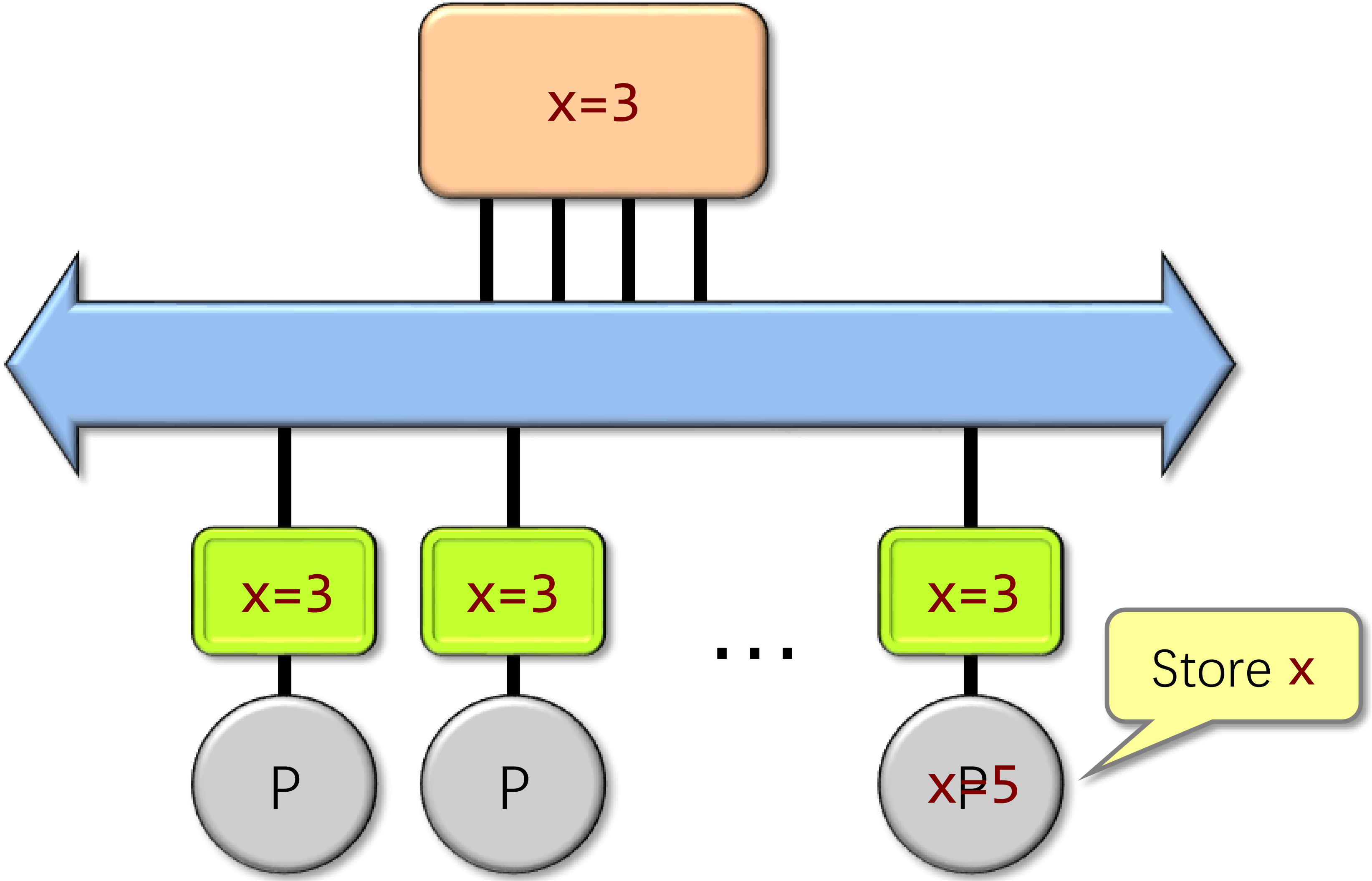

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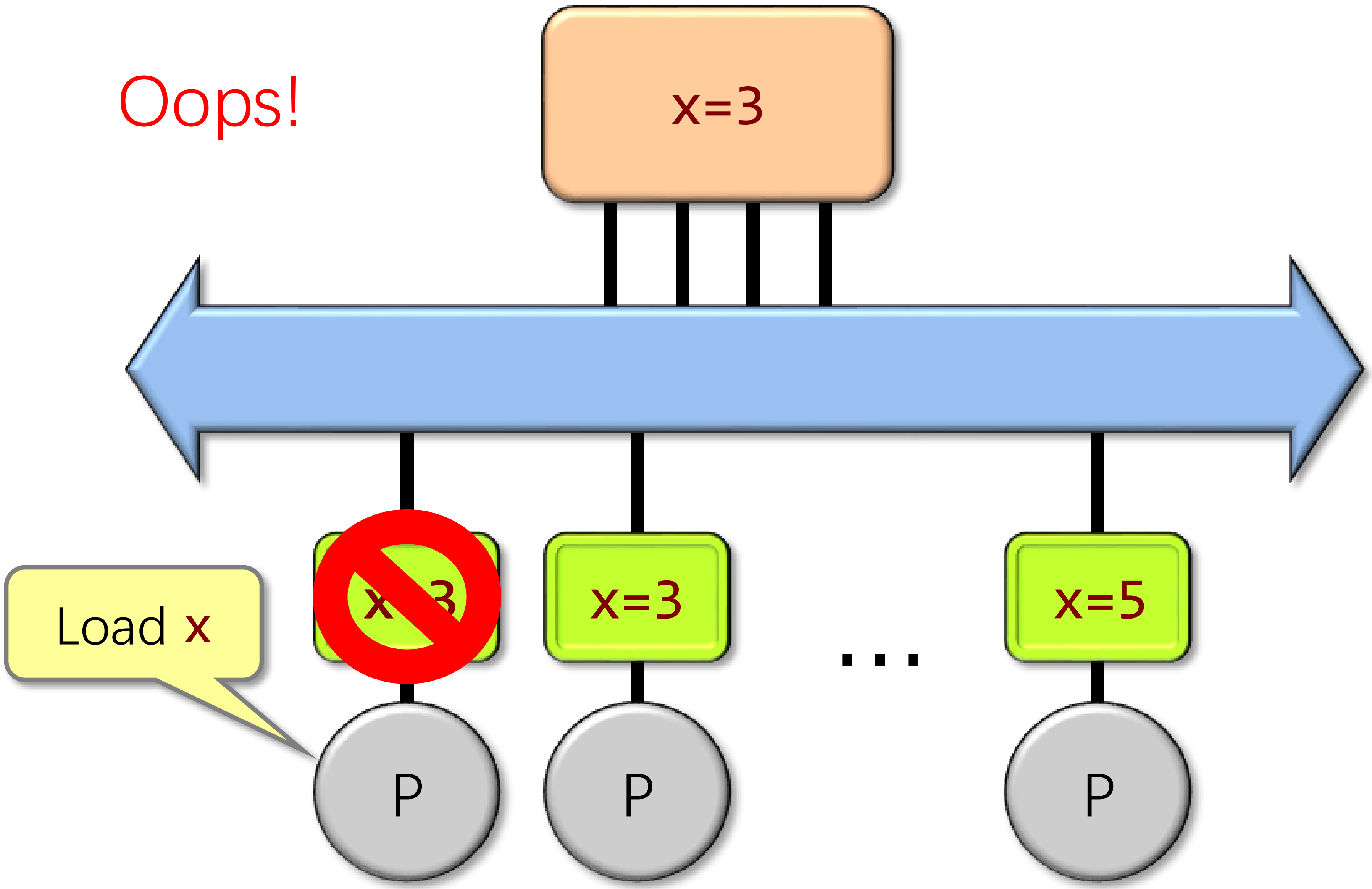
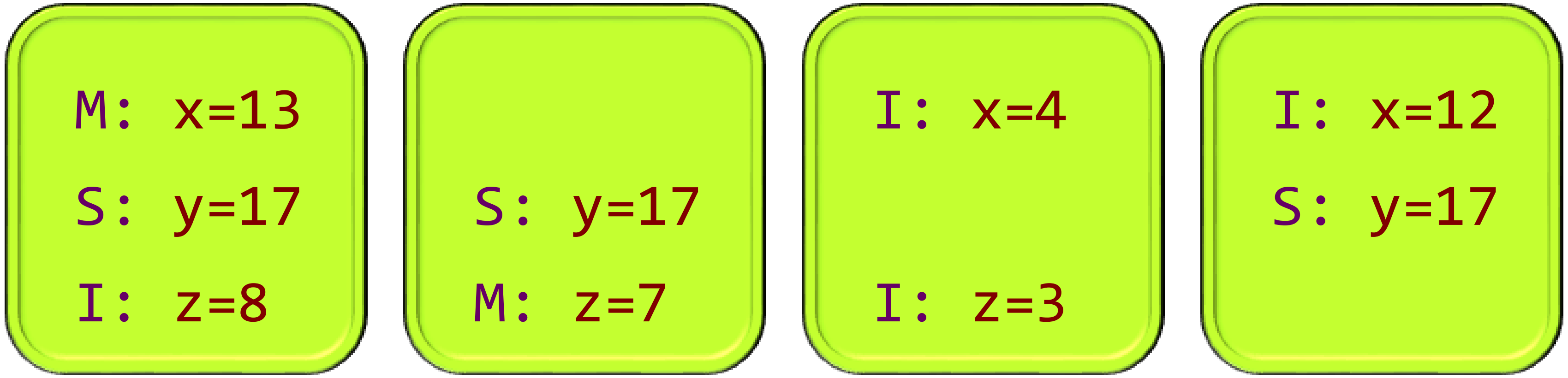


MSI Protocol

Each cache line is labeled with a state:

- **M**: cache block has been modified. No other caches contain this block in M or S.
- **S**: other caches may be sharing this block.
- **I**: cache block is invalid (same as not there).



Before a cache modifies a location, the hardware first invalidates all other copies.

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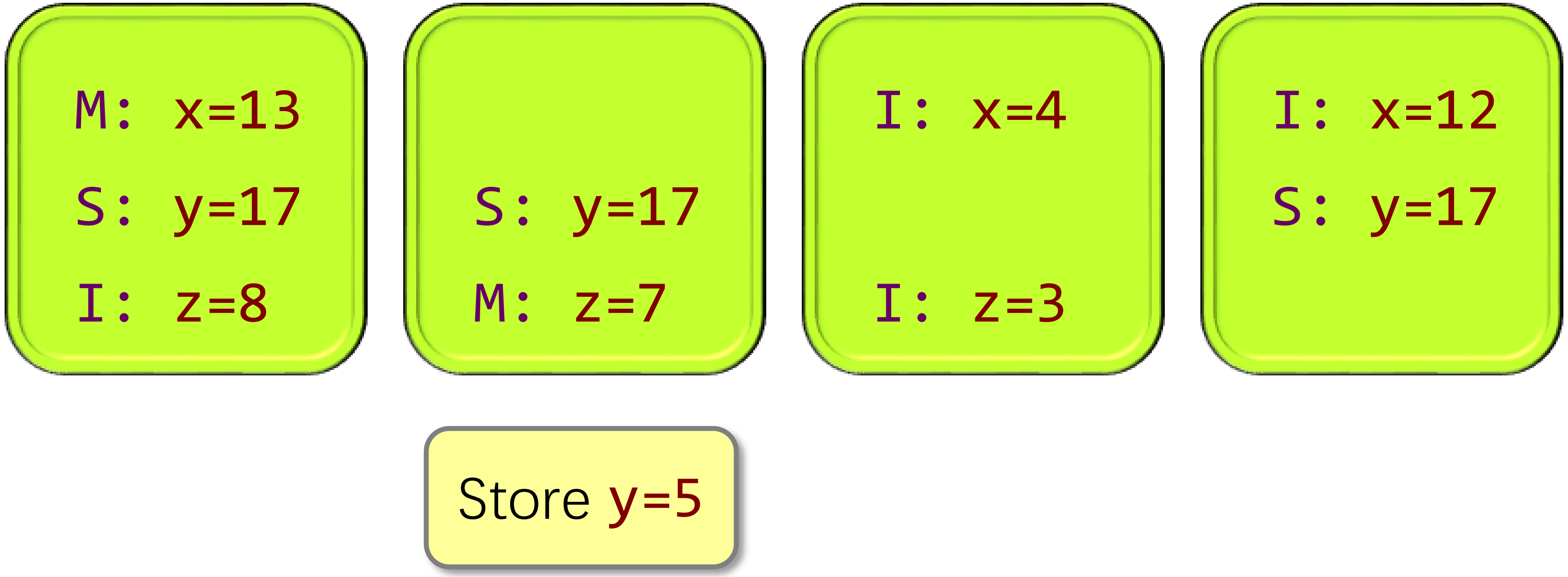

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M: x=13		I: x=4	I: x=12
S: y=17	S: y=17		S: y=17
I: z=8	M: z=7	I: z=3	

Store y=5

MSI Protocol

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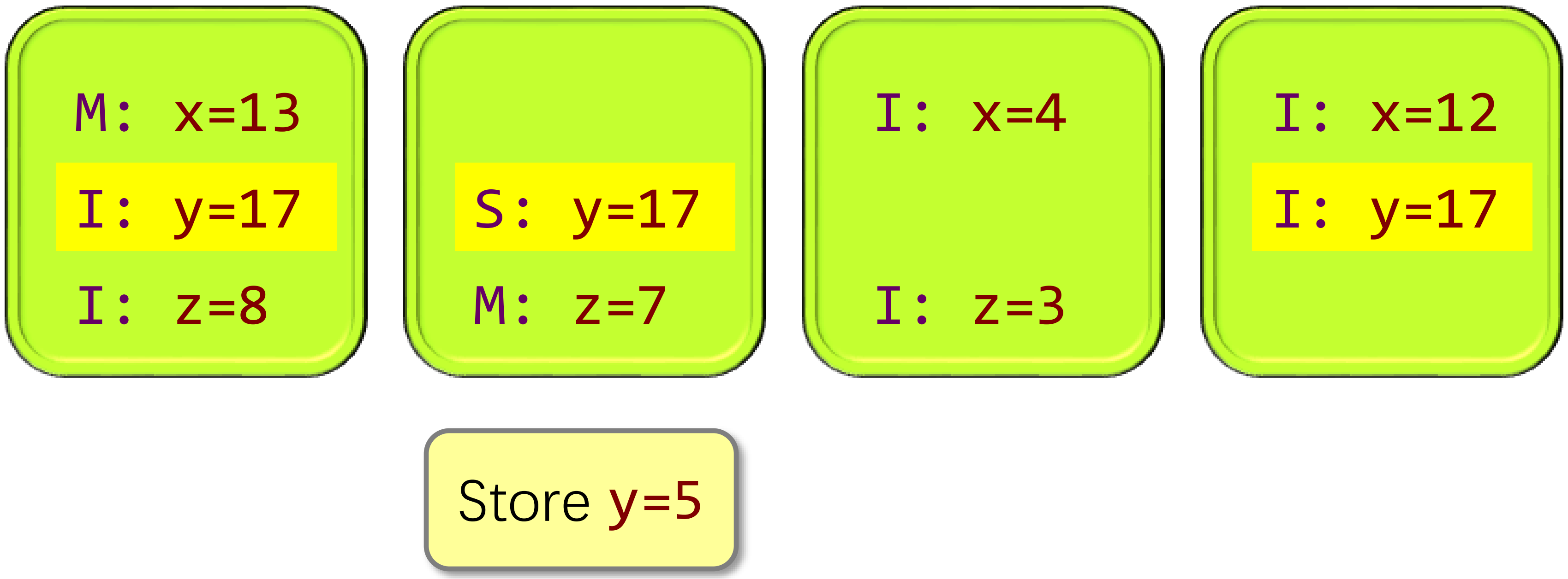

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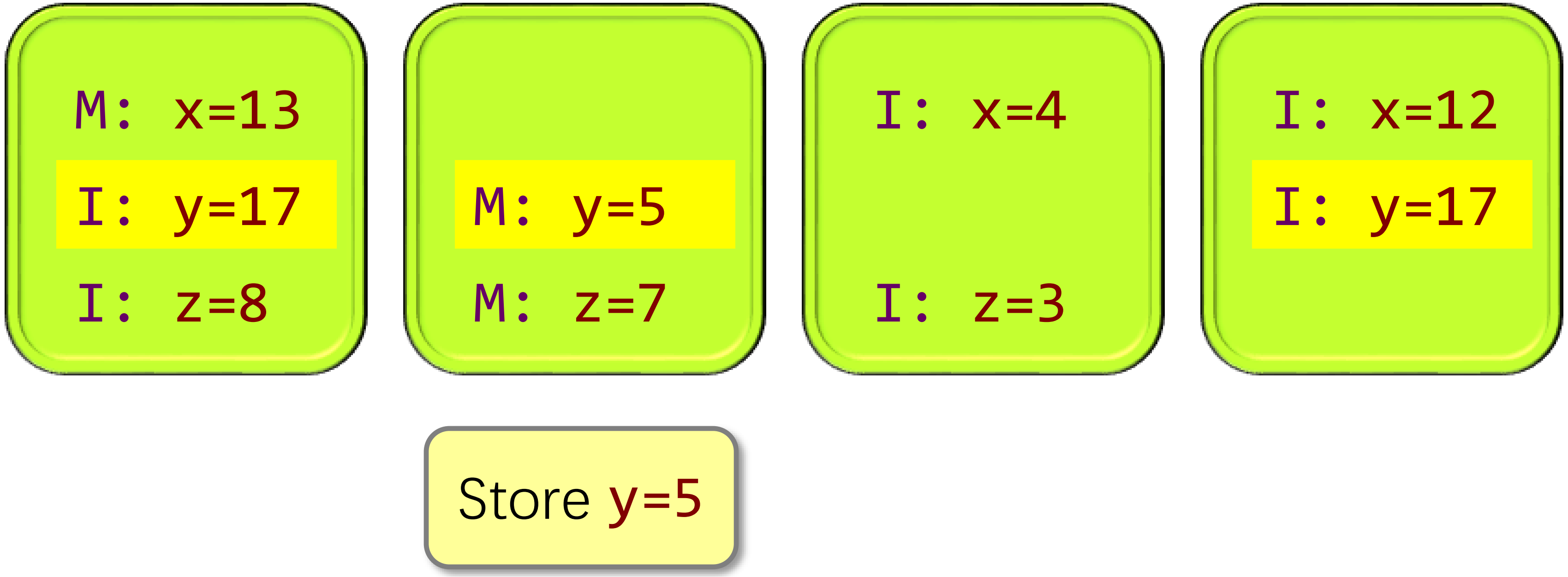

MSI Protocol

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`M: x=13`		`I: x=4`	`I: x=12`
`I: y=17`	`M: y=5`		`I: y=17`
`I: z=8`	`M: z=7`	`I: z=3`	

CONCURRENCY PLATFORMS

Concurrency Platforms

- Programming directly on processor cores is painful and error-prone
- A **concurrency platform** helps
  - abstract processor cores
  - handle synchronization and communication
  - perform load balancing
- Examples
  - Pthreads and WinAPI threads
  - Threading Building Blocks (TBB)
  - OpenMP
  - **Cilk**

Fibonacci Numbers

The Fibonacci numbers are the sequence $\langle 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, \cdots \rangle$, where each number is the sum of the previous two.

Recurrence:

$F_0 = 0,$

$F_1 = 1,$

$F_n = F_{n-1} + F_{n-2}$ for $n > 1$.

The sequence is named after **Leonardo di Pisa** (1170–1250 A.D.), also known as Fibonacci, a contraction of filius Bonaccii —"son of Bonaccio." Fibonacci's 1202 book Liber Abaci introduced the sequence to Western mathematics, although it had previously been discovered by Indian mathematicians.

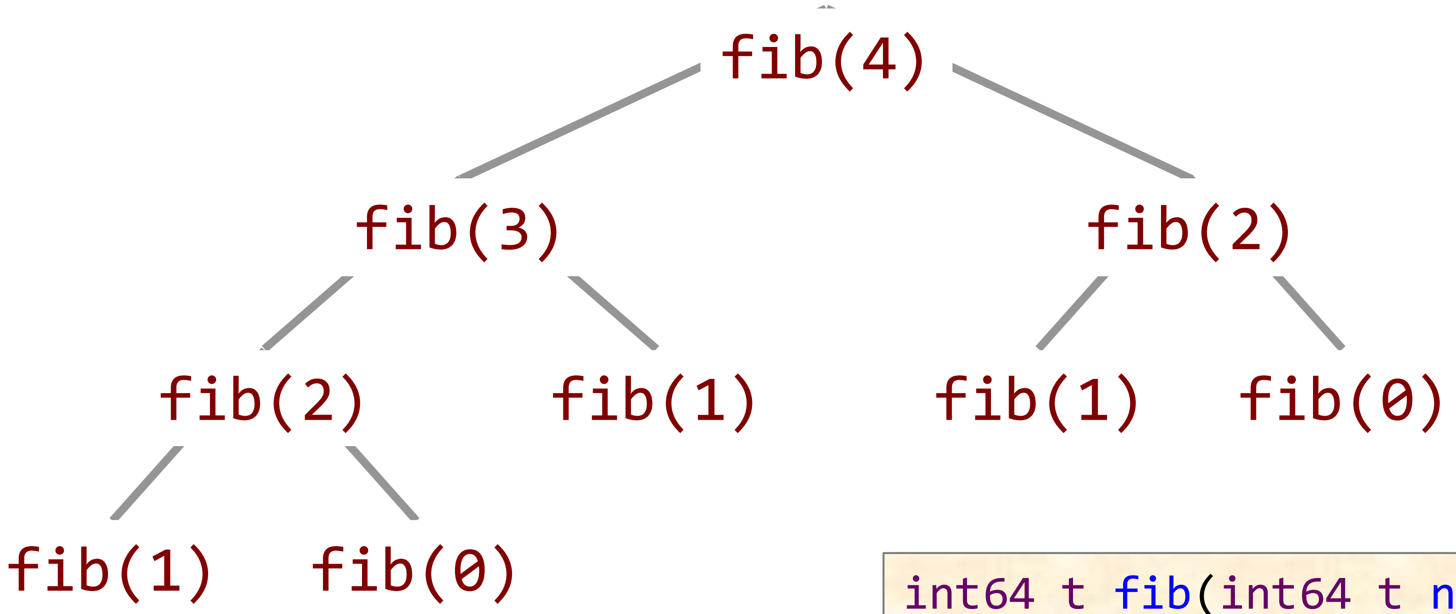
Fibonacci Program

```c
#include <inttypes.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

int main(int argc, char *argv[]) {
  int64_t n = atoi(argv[1]);
  int64_t result = fib(n);
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Disclaimer to Algorithms Police

This recursive program is a poor way to compute the nth Fibonacci number, but it provides a good didactic example.

Fibonacci Execution



Key idea for parallelization

`fib(n-1)` and `fib(n-2)` can be executed simultaneously without mutual interference

```
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}
```

Concurrency Platforms

- **Pthreads (& WinAPI Threads)**
- Threading Building Blocks
- OpenMP
- Cilk

Pthreads*

- Standard API for threading specified by ANSI/IEEE POSIX 1003.1-2008
- Do-it-yourself concurrency platform
- Built as a library of functions with “special” non-C semantics
- Each thread implements an abstraction of a processor, which are multiplexed onto machine resources

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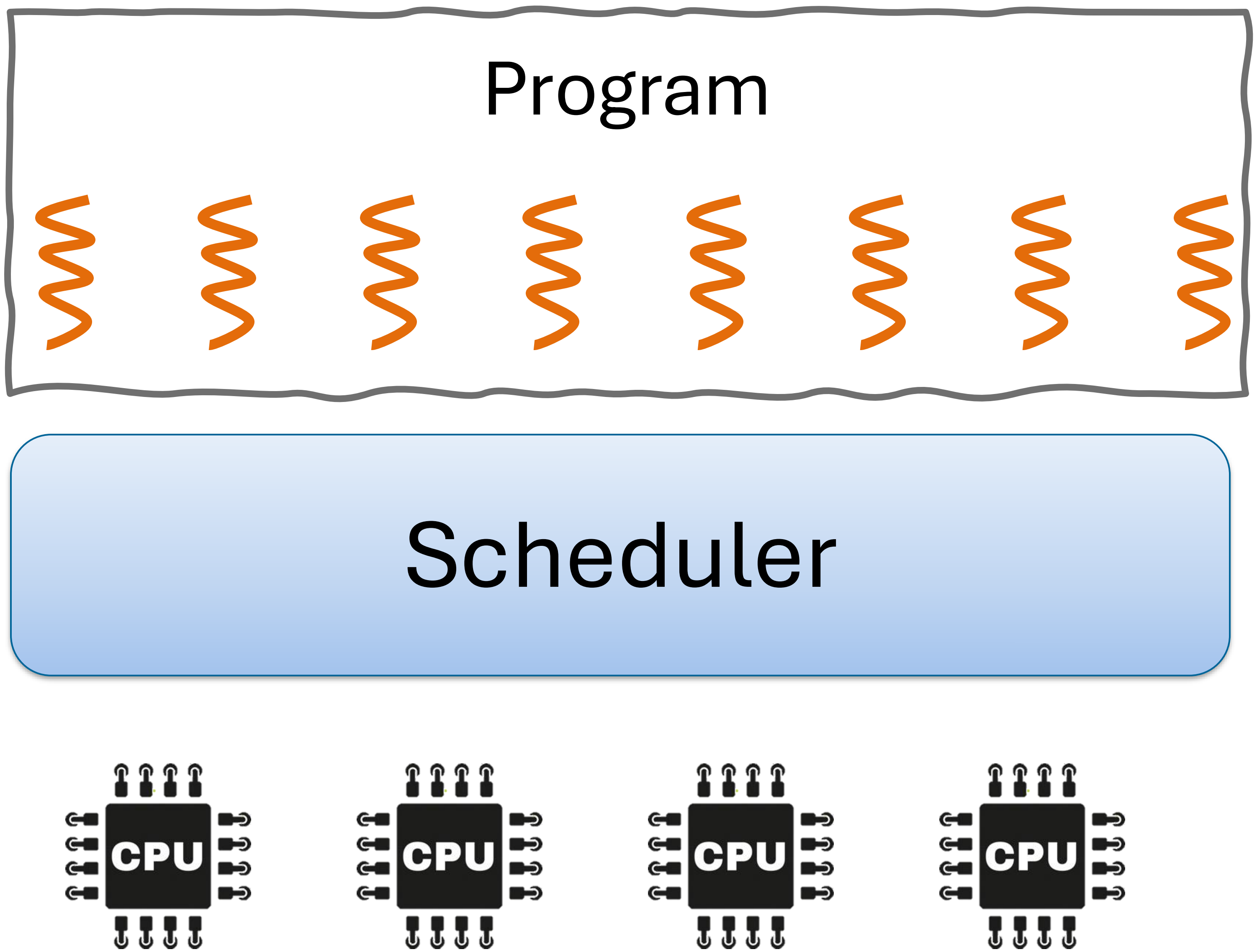
*WinAPI threads provide similar functionality.

Threading Abstraction

- The programmer specifies **threads**
- The scheduler **maps** each thread to a processor (e.g., whenever a processor is available)



Pthreads*

- Standard API for threading specified by ANSI/IEEE POSIX 1003.1-2008
- Do-it-yourself concurrency platform
- Built as a library of functions with “special” non-C semantics
- Each thread implements an abstraction of a processor, which are multiplexed onto machine resources
- Threads communicate through shared memory
- Library functions mask the protocols involved in inter-thread coordination

---

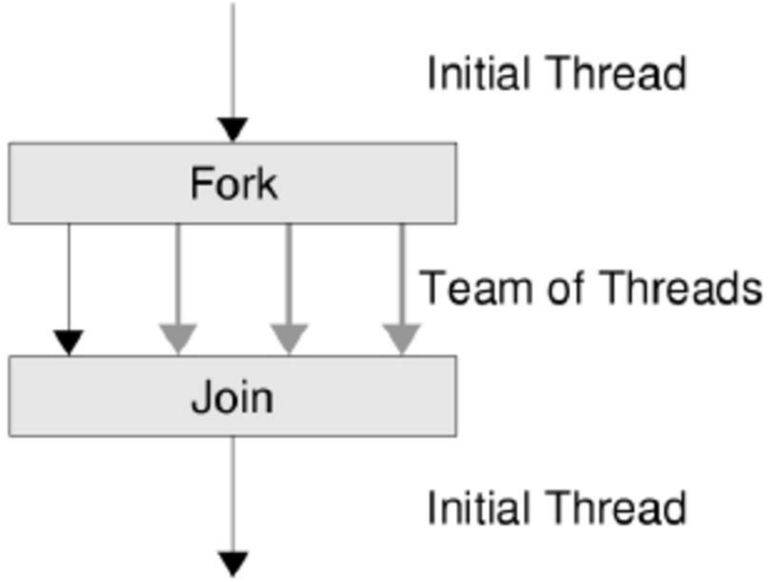
*WinAPI threads provide similar functionality.

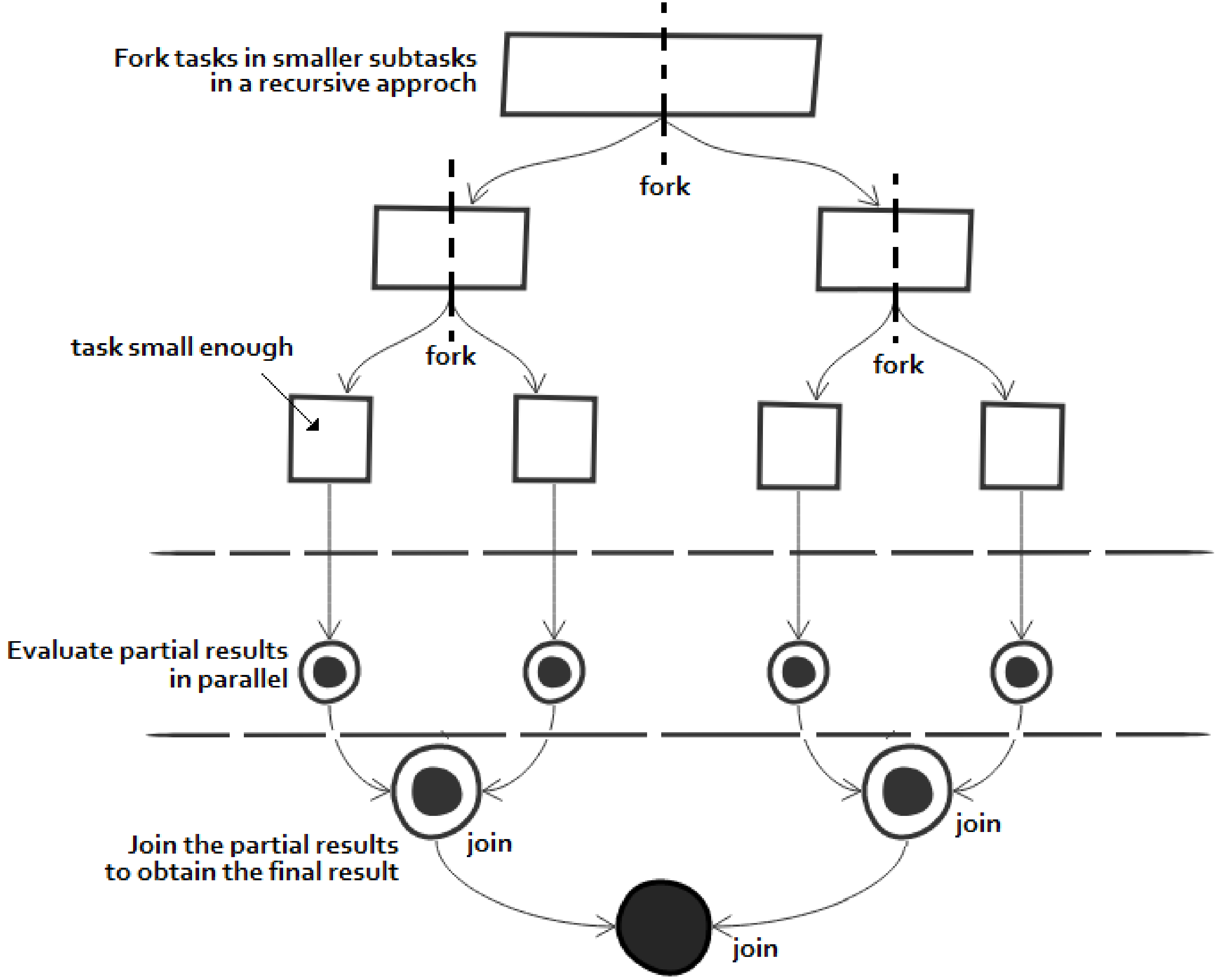
Key Pthread Functions

```
int pthread_create(
  pthread_t *thread,
    //returned identifier for the new thread
  const pthread_attr_t *attr,
    //object to set thread attributes (NULL for default)
  void *(*func)(void *),
    //routine executed after creation
  void *arg
    //a single argument passed to func
) //returns error status
```

```
int pthread_join(
  pthread_t thread,
    //identifier of thread to wait for
  void **status
    //terminating thread's status (NULL to ignore)
) //returns error status
```

fork-join Programming Model





Pthread fib Implementation

```c
#include <inttypes.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(void *ptr) {
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
  int64_t n = strtoul(argv[1], NULL, 0);
  if (n < 30) {
    result = fib(n);
  } else {
    args.input = n-1;
    status = pthread_create(&thread,
                            NULL,
                            thread_func,
                            (void*) &args);
    // main can continue executing
    if (status != NULL) { return 1; }
    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Pthread `fib` Implementation

Original code

```c
#include <inttypes.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(void *ptr) {
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
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}
```

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int main(int argc, char *argv[]) {
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Pthread fib Implementation

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void *thread_func(void *ptr) {
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  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

Structure for thread arguments

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
  int64_t n = strtoul(argv[1], NULL, 0);
  if (n < 30) {
    result = fib(n);
  } else {
    rgs.input = n-1;
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                            (void*) &args);
    // main can continue executing
    if (status != NULL) { return 1; }
    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
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  return 0;
}
```

Pthread fib Implementation

```c
#include <inttypes.h>
#include <pthread.h>
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}
```

Function called when thread is created

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
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  int status;
  int64_t result;

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    // main can continue executing
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    // wait for the thread to terminate
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    if (status != NULL) { return 1; }
    result += args.output;
  }
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         n, result);
  return 0;
}
```

Pthread `fib` Implementation

```c
#include <inttypes.h>
#include <pthread
#include <stdio.h
#include <stdlib.

int64_t fib(int64
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(void *ptr) {
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

No point in creating thread if there isn't enough to do

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
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Pthread fib Implementation

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  int64_t n = strtoul(argv[1], N
  if (n < 30) {
    result = fib(n);
  } else {
    args.input = n-1;
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    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Marshal input argument to thread

Pthread fib Implementation

```c
#include <inttypes.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(void *ptr) {
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
  int64_t n = strtoul(argv[1], NULL, 0);
  if (n < 30) {
    result = fib(n);
  } else {
    args.input = n-1;
    status = pthread_create(&thread,
                            NULL,
                            thread_func,
                            (void*) &args);
    // main can continue executing
    if (status != NULL) { return 1; }
    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Create thread to execute fib(n–1)

Pthread fib Implementation

```c
#include <inttypes.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

Main program runs `fib(n–2)` in parallel.

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
  int64_t n = strtoul(argv[1], NULL, 0);
  if (n < 30) {
    result = fib(n);
  } else {
    args.input = n-1;
    status = pthread_create(&thread,
                            NULL,
                            thread_func,
                            (void*) &args);
    // main can continue executing
    if (status != NULL) { return 1; }
    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Pthread `fib` Implementation

```c
#include <inttypes.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(void *ptr) {
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

Block until the auxiliary thread finishes.

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
  int64_t n = strtoul(argv[1], NULL, 0);
  if (n < 30) {
    result = fib(n);
  } else {
    args.input = n-1;
    status = pthread_create(&thread,
                            NULL,
                            thread_func,
                            (void*) &args);
    // main can continue executing
    if (status != NULL) { return 1; }
    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Pthread fib Implementation

```c
#include <inttypes.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}

typedef struct {
  int64_t input;
  int64_t output;
} thread_args;

void *thread_func(void *ptr) {
  int64_t i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

```c
int main(int argc, char *argv[]) {
  pthread_t thread;
  thread_args args;
  int status;
  int64_t result;

  if (argc < 2) { return 1; }
  int64_t n = strtoul(argv[1], NULL, 0);
  if (n < 30) {
    result = fib(n);
  } else {
    args.input = n-1;
    status = pthread_create(&thread,
                            NULL,
                            thread_func,
                            (void*) &args);
    // main can continue executing
    if (status != NULL) { return 1; }
    result = fib(n-2);
    // wait for the thread to terminate
    status = pthread_join(thread, NULL);
    if (status != NULL) { return 1; }
    result += args.output;
  }
  printf("Fibonacci of %" PRId64 " is %" PRId64 ".\n",
         n, result);
  return 0;
}
```

Add the results together to produce the final output.

Issues with Pthreads

Overhead	The cost of creating a thread $>10^4$ cycles ⇒ coarse-grained concurrency. (Thread pools can help.)

Issues with Pthreads

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Issues with Pthreads

Overhead	The cost of creating a thread >10^4 cycles ⇒ coarse-grained concurrency. (Thread pools can help.)
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Issues with Pthreads

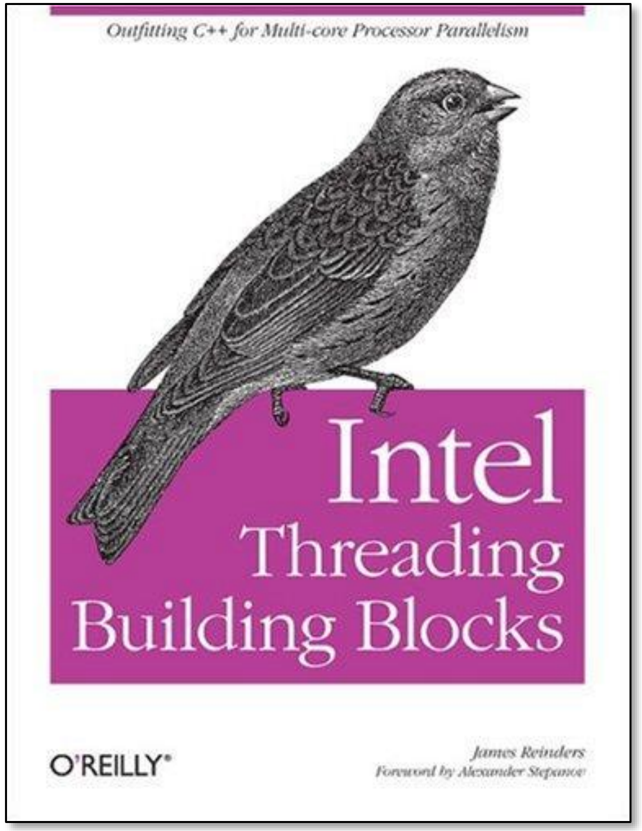
Overhead	The cost of creating a thread $>10^4$ cycles ⇒ coarse-grained concurrency. (Thread pools can help.)
Scalability	Fibonacci code gets at most about 1.5 speedup for 2 cores. Need a rewrite for more cores
Modularity	The Fibonacci logic is no longer neatly encapsulated in the `fib()` function
Code Simplicity	Programmers must marshal arguments (shades of 1957!) and engage in error-prone protocols for load-balance

Concurrency Platforms

- Pthreads (& WinAPI Threads)
- Threading Building Blocks
- OpenMP
- Cilk

Threading Building Blocks

- Developed by Intel, as a C++ library that runs on native threads
- Programmer specifies **tasks** rather than threads
- Tasks are automatically load balanced across the threads using a **work-stealing** algorithm inspired by Cilk at MIT
- Focus on performance



Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                          FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                          FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                         FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                         FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

A computation organized as explicit tasks.

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                 FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                         FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                         FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

FibTask has an input parameter n and an output parameter sum.

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* s
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                     FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                     FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

The **execute()** function performs the computation when the task is started.

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                 FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
            << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                         FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                         FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

Recursively create two child tasks a and b.

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                        FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                        FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

Set the number of tasks to wait for (2 children + 1 implicit for bookkeeping).

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                     FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                     FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

Start task b.

```
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child()
                         FibTask(n-1, &x
      FibTask& b = *new( allocate_chil   ) )
                         FibTask(n-2,   y));
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

Start task a, and wait for both a and b to finish.

```
#in        stdint>
#i         <iostream>
#          e "tbb/task.h"

   main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_c     () )
                         FibTask(     &x);
      FibTask& b = *new( alloca   child() )
                         FibT   (n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_f   all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

Add the results together to produce the final output.

```
#i       cstdint>
       e <iostream>
    ude "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Fibonacci in TBB

```cpp
using namespace tbb;
class FibTask: public task {
public:
  const int64_t n;
  int64_t* const sum;
  FibTask(int64_t n_, int64_t* sum_) :
          n(n_), sum(sum_) {}

  task* execute() {
    if( n < 2 ) {
      *sum = n;
    } else {
      int64_t x, y;
      FibTask& a = *new( allocate_child() )
                         FibTask(n-1, &x);
      FibTask& b = *new( allocate_child() )
                         FibTask(n-2, &y);
      set_ref_count(3);
      spawn(b);
      spawn_and_wait_for_all(a);
      *sum = x + y;
    }
    return NULL;
  }
};
```

Create root task; spawn and wait.

```cpp
#include <cstdint>
#include <iostream>
#include "tbb/task.h"

int main(int argc, char *argv[]) {
  int64_t res;
  if (argc < 2) { return 1; }
  int64_t n =
    strtoul(argv[1], NULL, 0);
  FibTask& a = *new(task::allocate_root())
                  FibTask(n, &res);
  task::spawn_root_and_wait(a);

  std::cout << "Fibonacci of " << n
       << " is " << res << std::endl;
  return 0;
}
```

Other TBB Features

- TBB provides many C++ templates to express common patterns simply
  - e.g. `parallel_for` for loop parallelism,
  - e.g. `parallel_reduce` for data aggregation,
  - e.g. `pipeline` and `filter` for software pipelining
- TBB provides concurrent container classes, which allow multiple threads to safely access and update items in the container concurrently
- TBB also provides a variety of mutual-exclusion library functions, including locks and atomic updates

CONCURRENCY PLATFORMS

- Pthreads (& WinAPI Threads)
- Threading Building Blocks
- OpenMP
- Cilk

OpenMP

- Specification by an industry consortium
- Several compilers available, both open-source and proprietary, including GCC, ICC, Clang, and Visual Studio
- Linguistic extensions to C/C++ and Fortran in the form of compiler **pragmas**
- Runs on top of native threads
- Supports loop parallelism, task parallelism, and pipeline parallelism

Fibonacci in OpenMP

```c
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x, y;
#pragma omp task shared(x,n)
    x = fib(n-1);
#pragma omp task shared(y,n)
    y = fib(n-2);
#pragma omp taskwait
    return (x + y);
  }
}
```

Compiler directive.

Fibonacci in OpenMP

```
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x, y;
#pragma omp task shared(x,n)
    x = fib(n-1);
#pragma omp task shared(y,n)
    y = fib(n-2);
#pragma omp taskwait
    return (x + y);
  }
}
```

The following statement is an independent task.

Fibonacci in OpenMP

```
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x, y;
#pragma omp task shared(x,n)
    x = fib(n-1);
#pragma omp task shared(y,n)
    y = fib(n-2);
#pragma omp taskwait
    return (x + y);
  }
}
```

Sharing of memory is managed explicitly.

Fibonacci in OpenMP

```
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x, y;
#pragma omp task shared(x,n)
    x = fib(n-1);
#pragma omp task shared(y,n)
    y = fib(n-2);
#pragma omp taskwait
    return (x + y);
  }
}
```

Wait for the two tasks to complete before continuing.

Fibonacci in OpenMP

- OpenMP provides many pragma directives to express common patterns
  - e.g. `parallel for` for loop parallelism
  - e.g. `reduction` for data aggregation
  - e.g. directives for scheduling and data sharing
- OpenMP supplies a variety of synchronization constructs,
  - e.g. barriers, atomic updates, mutual-exclusion (mutex) locks

Concurrency Platforms

- Pthreads (& WinAPI Threads)
- Threading Building Blocks
- OpenMP
- Cilk

Cilk

- Award-winning multithreading language developed at MIT
- Linguistic extensions to C/C++ to support **fork-join** parallelism
- Features a provably efficient **work-stealing** scheduler
- Provides a reducer linguistic interface for parallelizing code with global variables

OpenCilk

- This course will be using the **OpenCilk** compiler
  - OpenCilk is based on LLVM
    - developed at MIT by Tao B. Schardl, William S. Moses, and Charles E. Leiserson
  - OpenCilk's compiler can generally produce better code than can other compilers for parallel-language constructs
  - The OpenCilk runtime system is based on Cheetah
    - developed by I-Ting Angelina Lee at Washington University in St. Louis
  - Tools: the Cilksan race detector and the Cilkscale scalability analyzer

Nested Parallelism in Cilk

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```

The named child function may execute in parallel with the parent caller.

Control cannot pass this point until all spawned children have returned.

Loop Parallelism in Cilk

Example: in-place **matrix transpose**

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \Rightarrow A^T = \begin{pmatrix} a_{11} & a_{21} & \cdots & a_{n1} \\ a_{12} & a_{22} & \cdots & a_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1n} & a_{2n} & \cdots & a_{nn} \end{pmatrix}$$

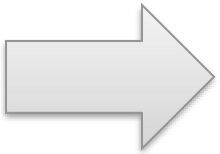
The iterations of a `cilk_for` loop execute in parallel

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Serial Semantics

Cilk source

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```



serial projection

```
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x, y;
    x = fib(n-1);
    y = fib(n-2);

    return (x + y);
  }
}
```

The serial projection of a Cilk program is always a legal interpretation of the program's semantics.

Remember, Cilk keywords grant permission for parallel execution. They do not command parallel execution.

To obtain the serial projection:

```
#define cilk_for for
#define cilk_spawn
#define cilk_scope
```

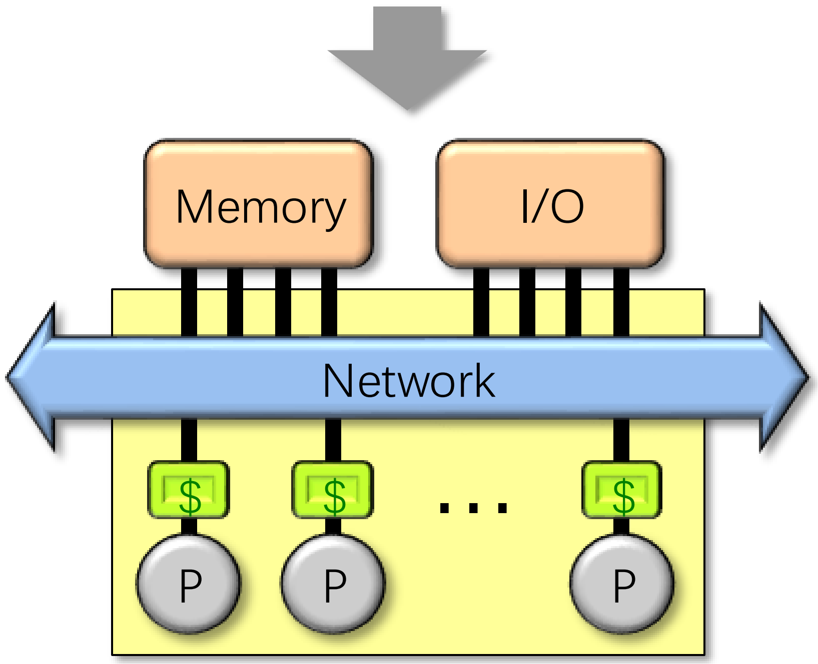
Scheduling

- Cilk allows the programmer to express logical parallelism in an application

- The Cilk scheduler maps the executing program onto the processor cores dynamically at runtime

- Cilk's **work-stealing** scheduling algorithm is provably efficient

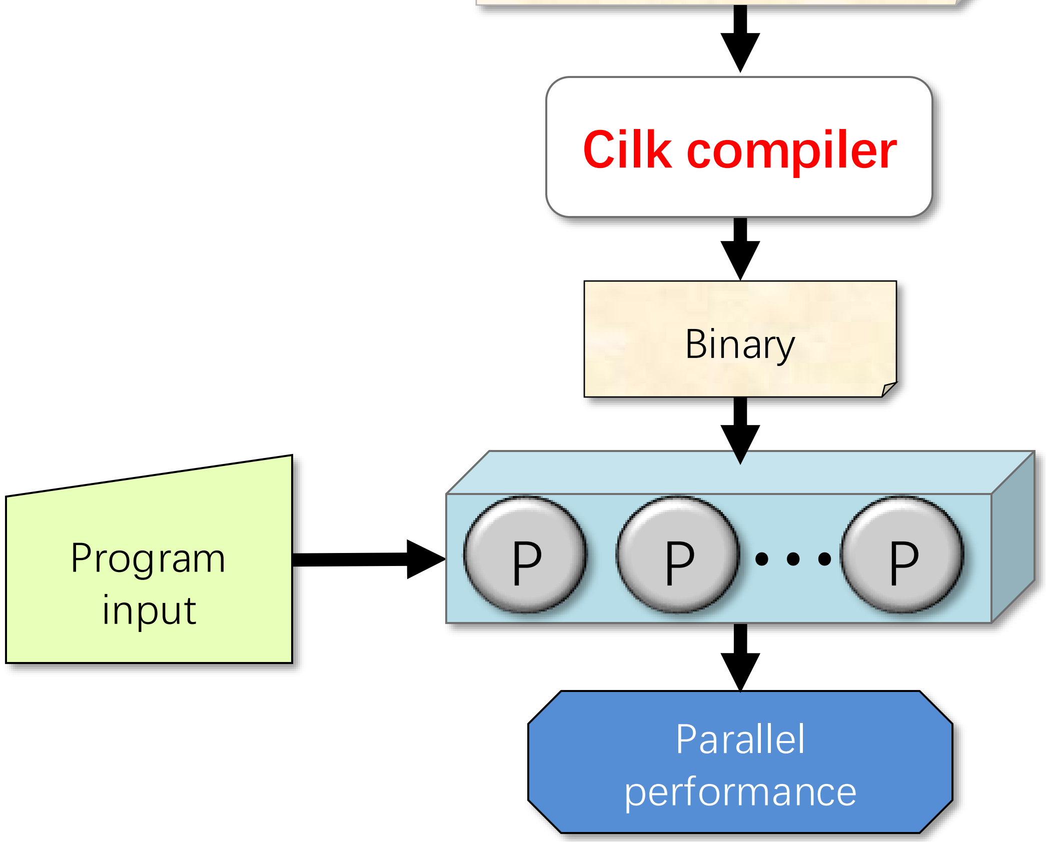
```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```



Cilk Platform

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```

Cilk source



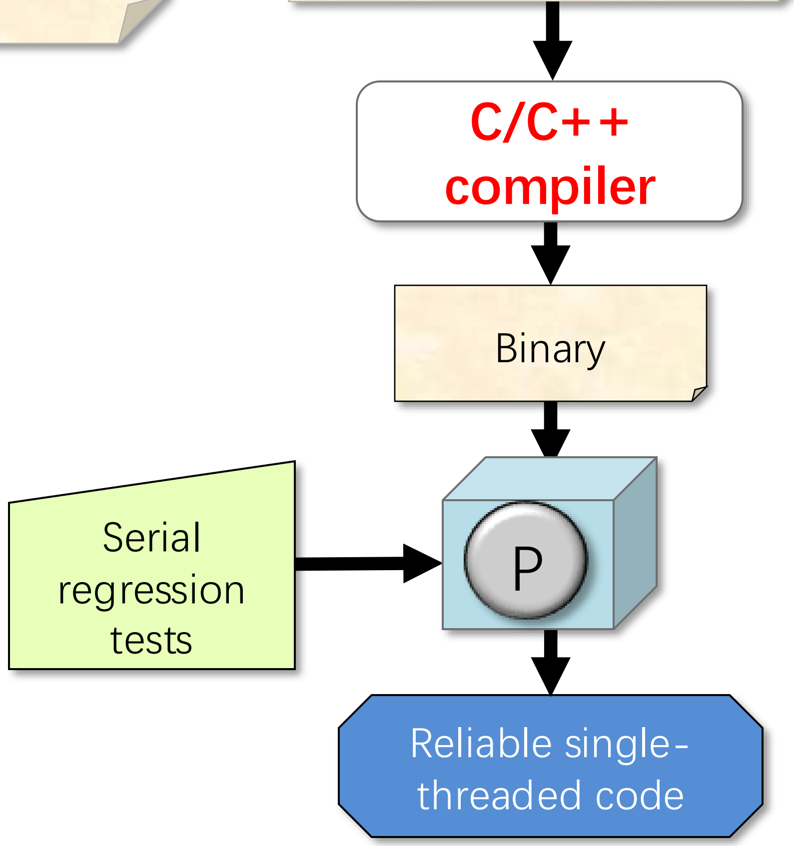
Serial Testing

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```

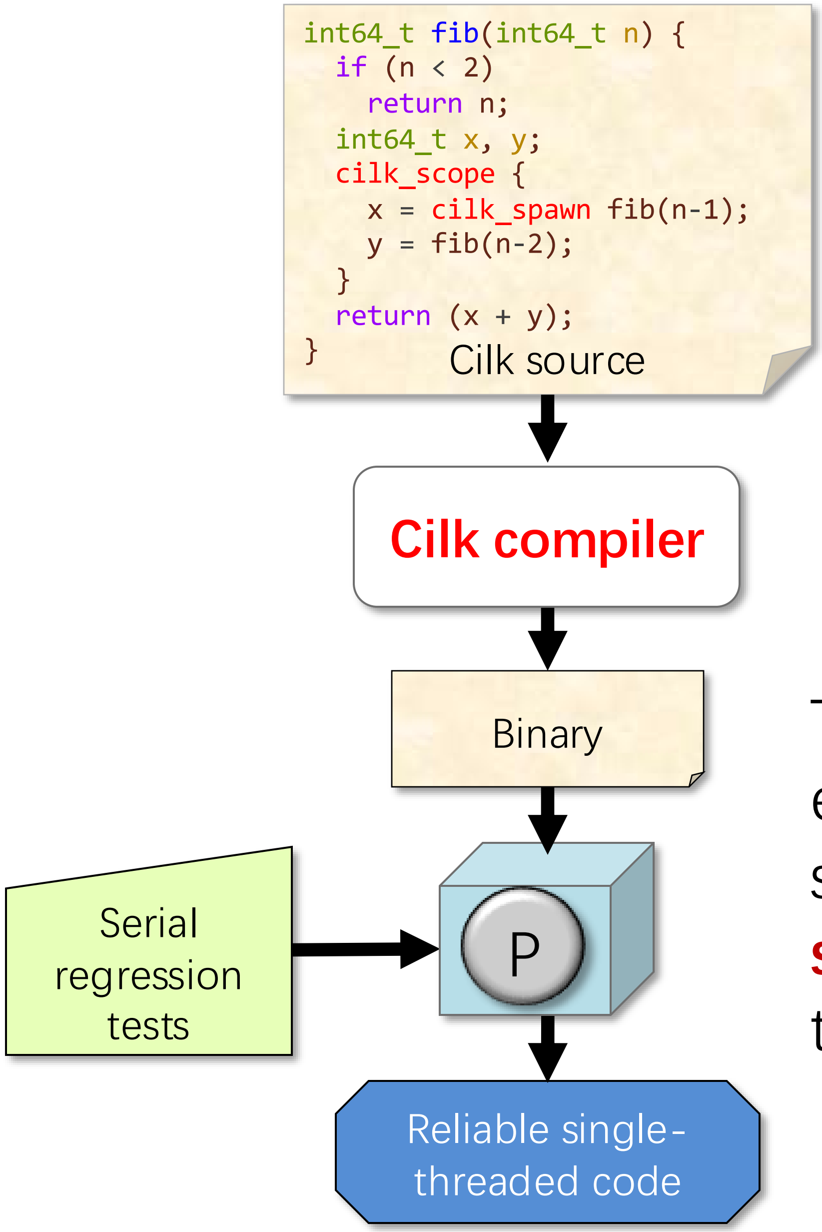
Cilk source

```
int64_t fib(int64_t n) {
  if (n < 2) { return n; }
  else {
    int64_t x = fib(n-1);
    int64_t y = fib(n-2);
    return (x + y);
  }
}
```

Serial projection



Alternative Serial Testing

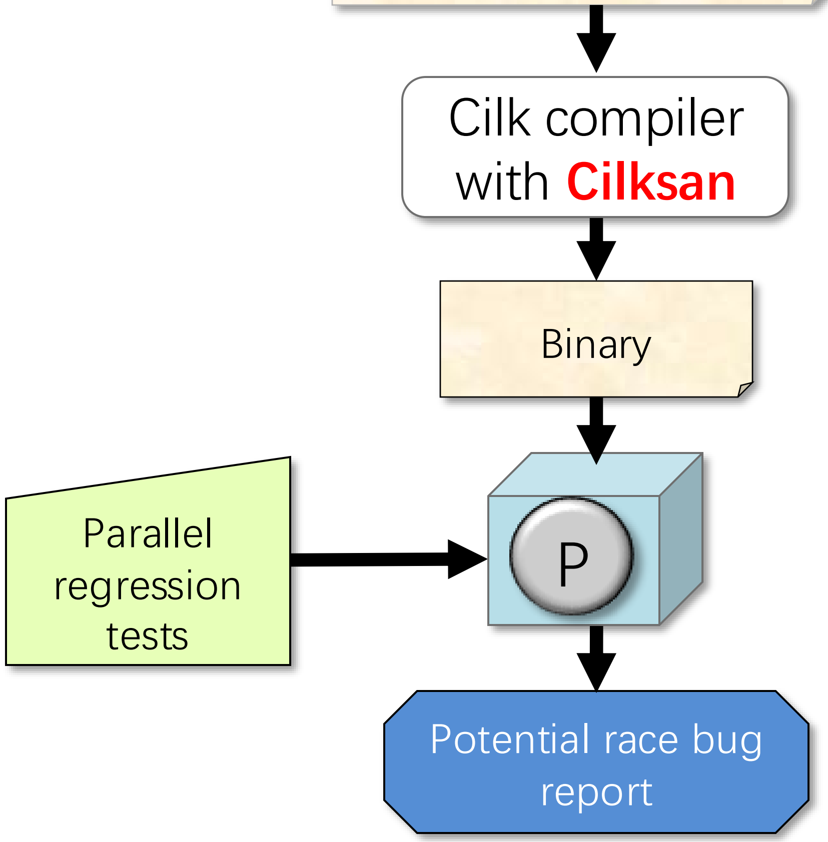


The parallel program executing on one core should behave **exactly the same** as the execution of the serial projection

Parallel Testing

```
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```

Cilk source

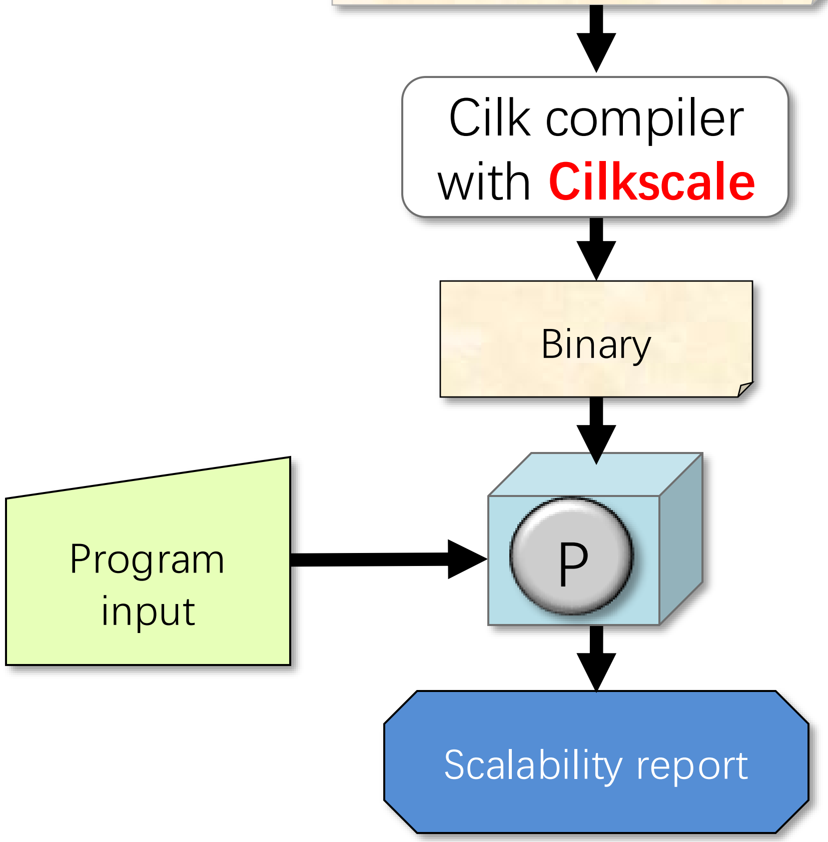


Cilksan finds and localizes race bugs

Scalability Analysis

```c
int64_t fib(int64_t n) {
  if (n < 2)
    return n;
  int64_t x, y;
  cilk_scope {
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
  }
  return (x + y);
}
```

Cilk source



How much parallelism?

Cilkscale analyzes how well your program will scale to larger machines

Summary

- Processors today have multiple cores, and obtaining high performance requires parallel programming
- Programming directly on processor cores is painful and error-prone
  - Concurrency platforms simplify programming for you
- Cilk simplifies parallel programming, and performs provably efficiently
- Project 2: Parallel simulation & rendering using Cilk