6.172 Performance Engineering of Software Systems

LECTURE 12
Multicore Programming

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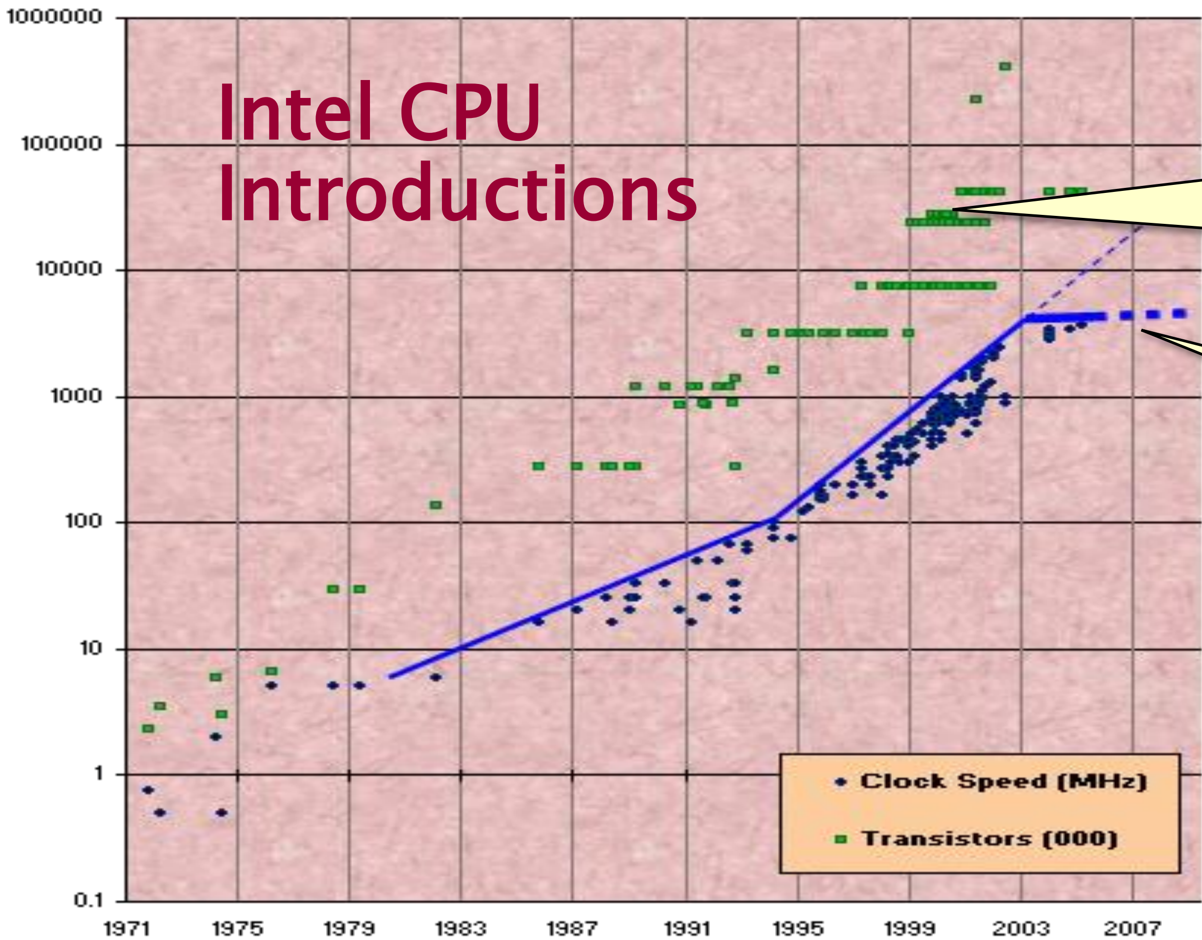
October 21, 2010

Moore's Law

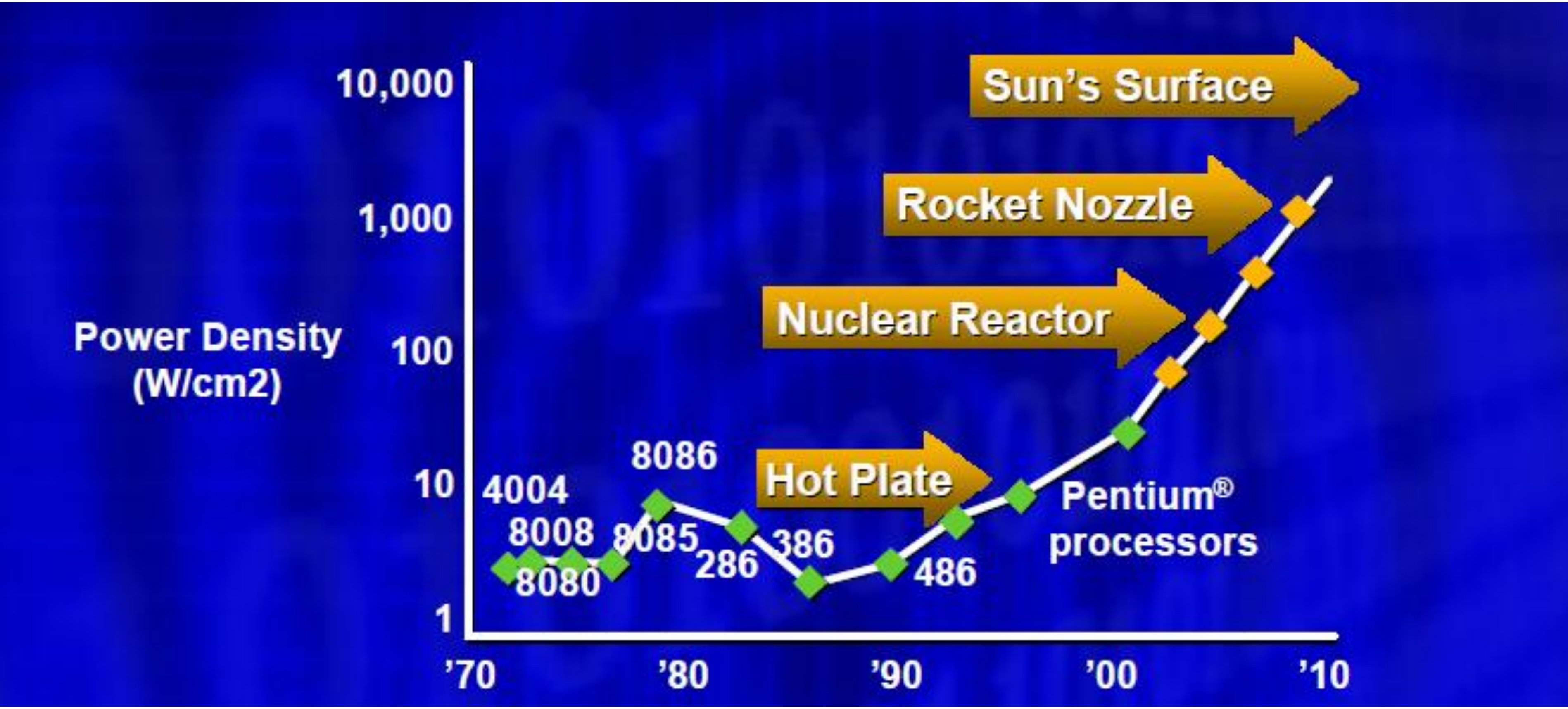


Transistor count is still rising, …

but clock speed is bounded at ~5GHz.

Source: Herb Sutter, "The free lunch is over: a fundamental turn toward concurrency in software," *Dr. Dobb's Journal*, 30(3), March 2005.

Power Density



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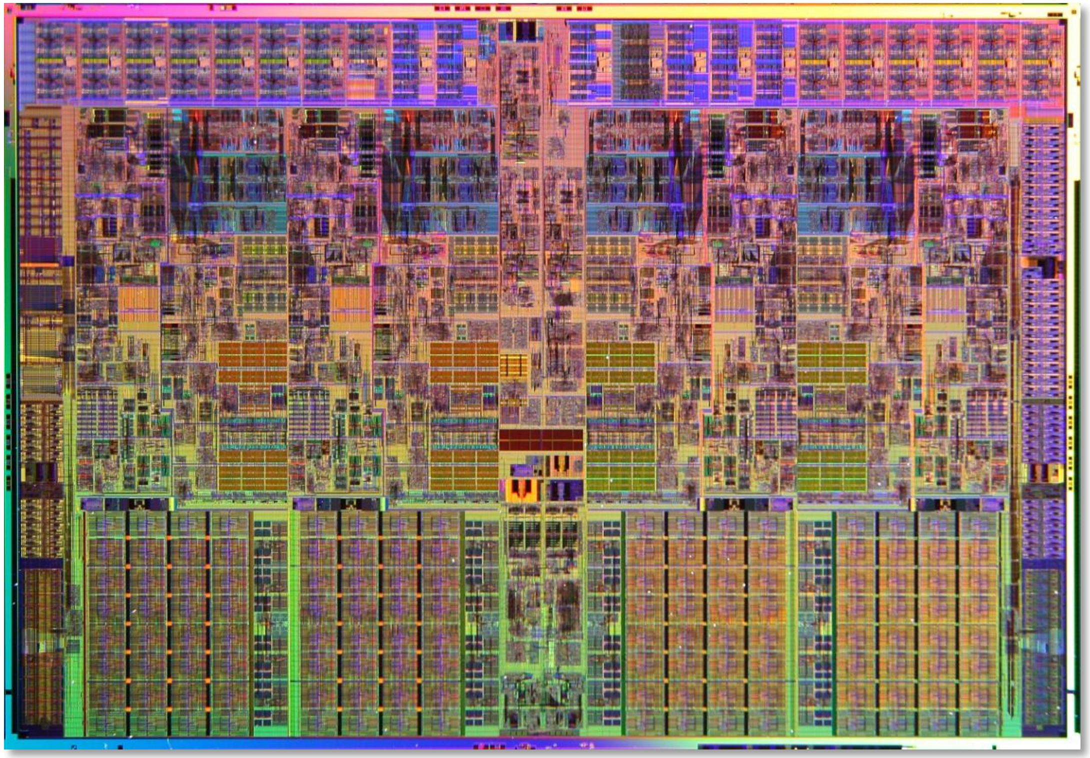
Source: Patrick Gelsinger, *Intel Developer's Forum*, Intel Corporation, 2004.

Vendor Solution



Intel Core i7 processor

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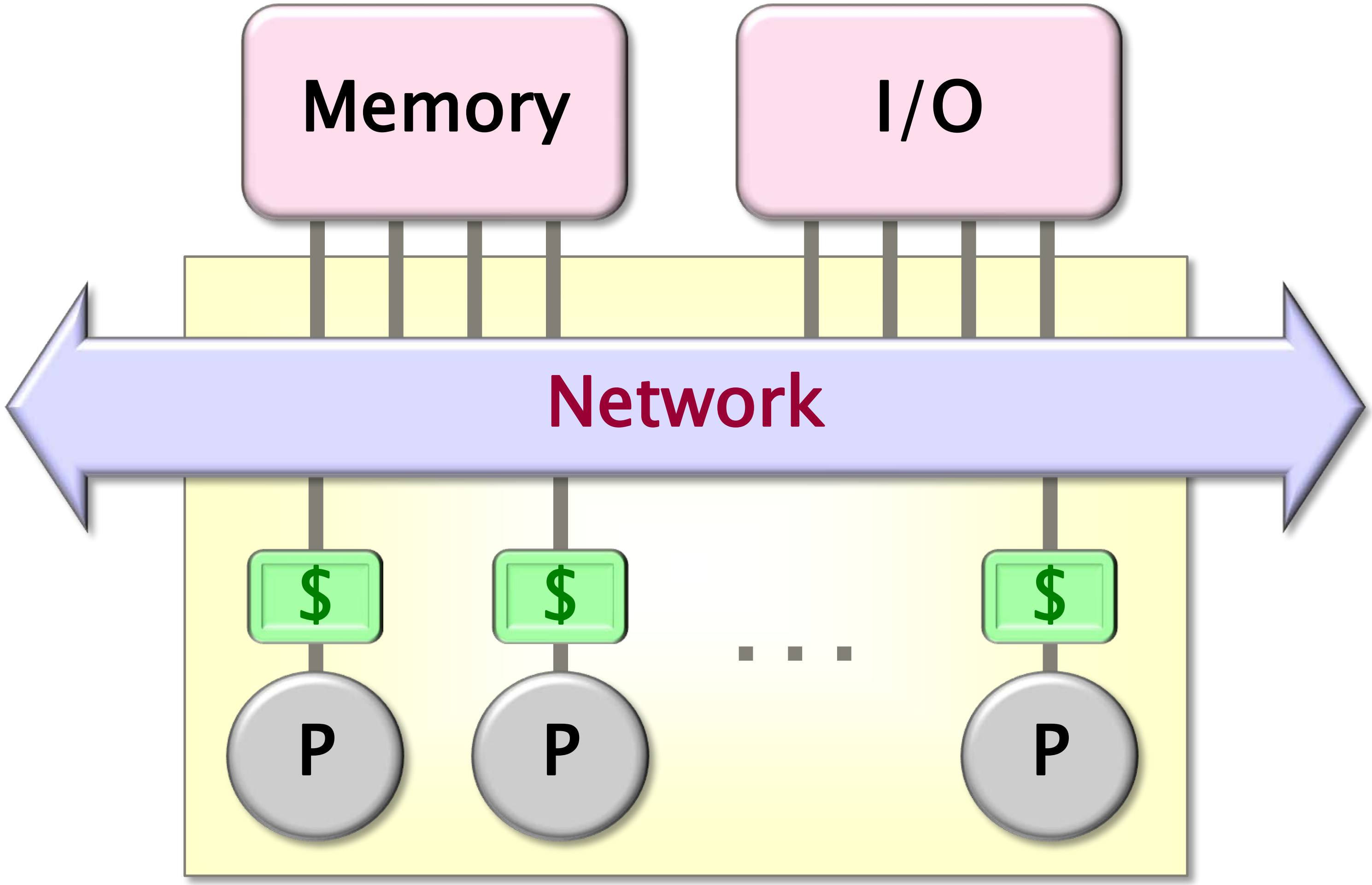
- To scale performance, put many processing cores on the microprocessor chip.
- Each generation of Moore's Law potentially doubles the number of cores.

Abstract Multicore Architecture



Chip Multiprocessor (CMP)

OUTLINE

- Shared-Memory Hardware
- Concurrency Platforms
  - Pthreads (and WinAPI Threads)
  - Threading Building Blocks
  - OpenMP
  - Cilk++
- Race Conditions

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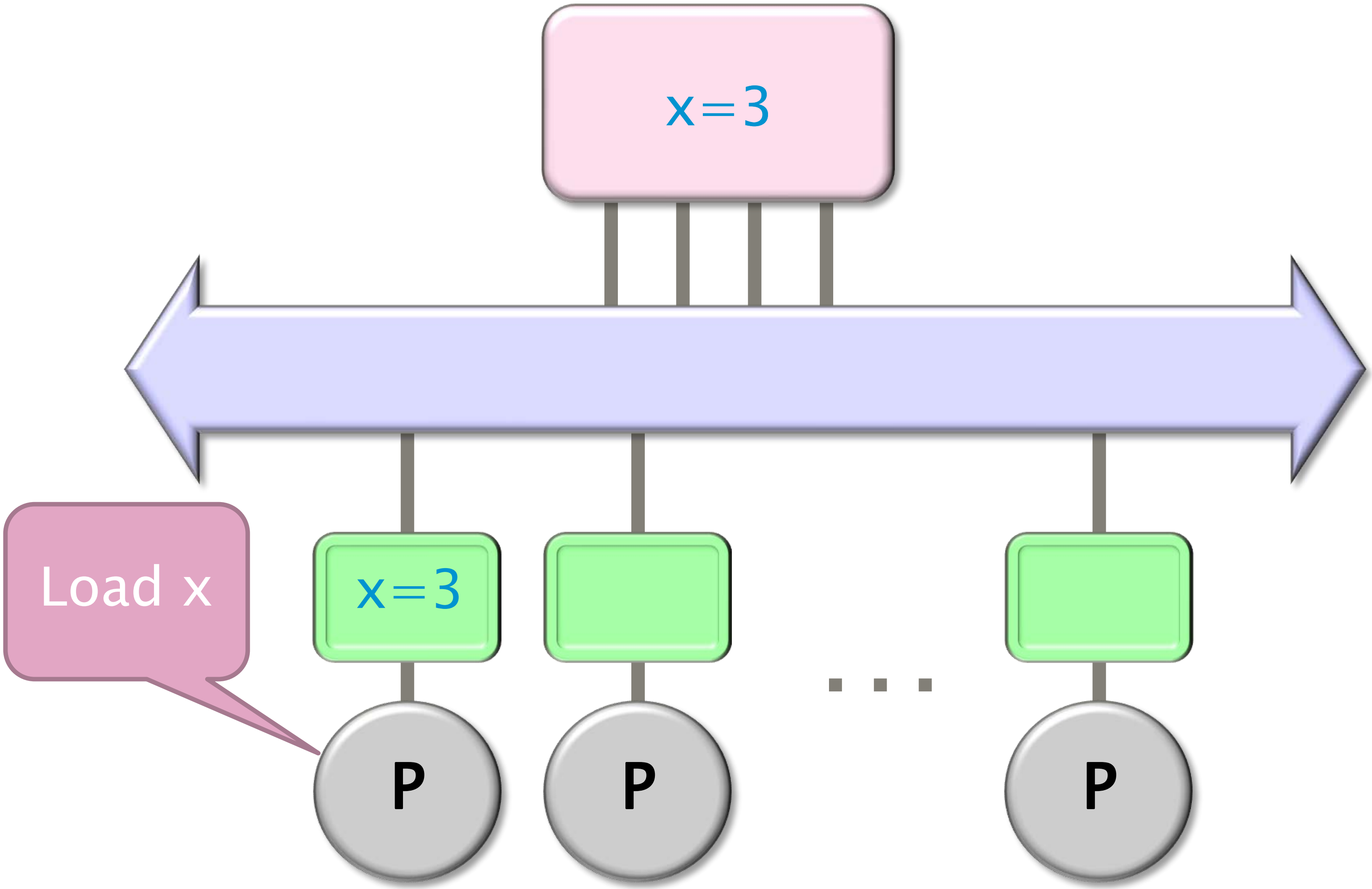
Cache Coherence



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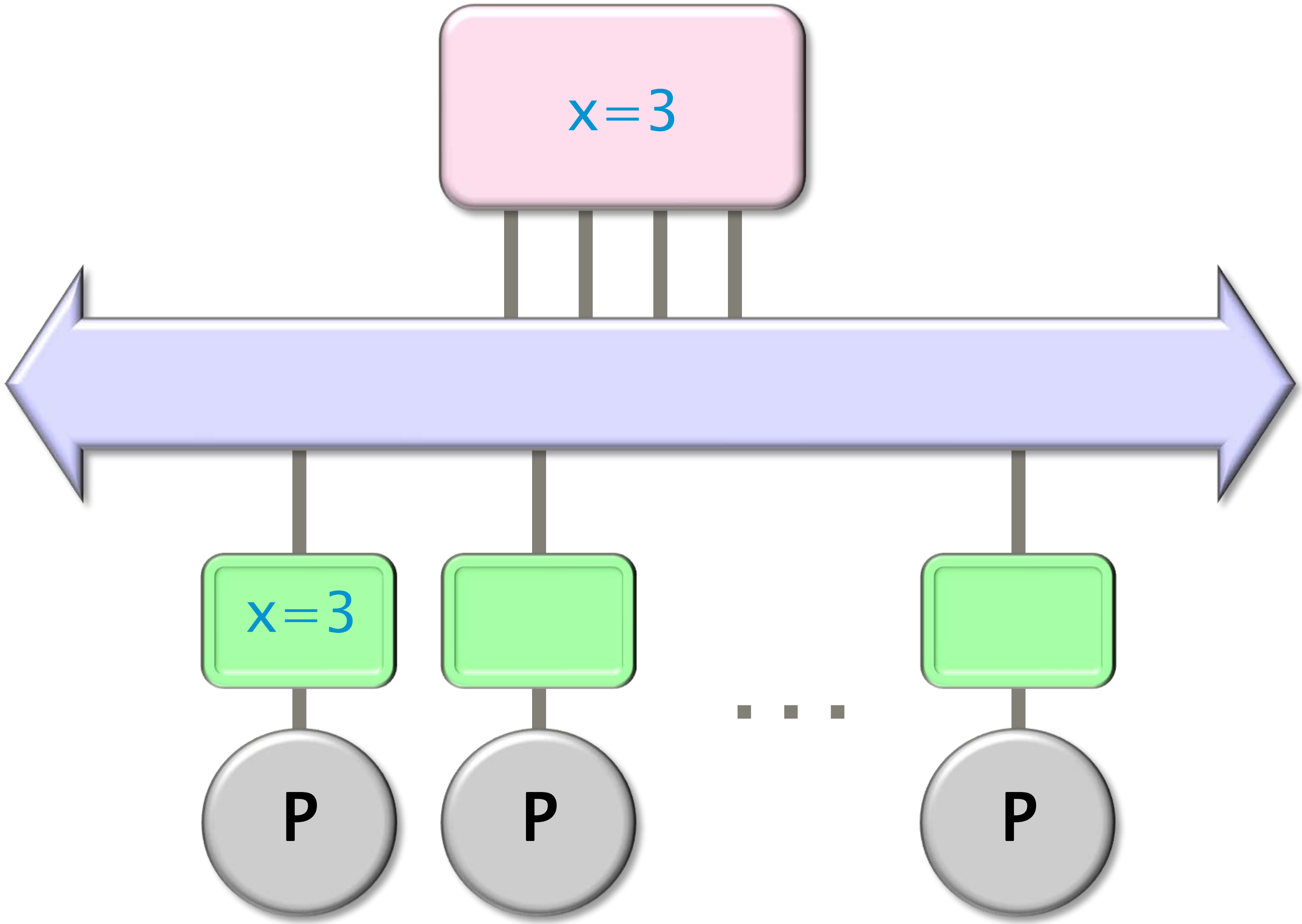

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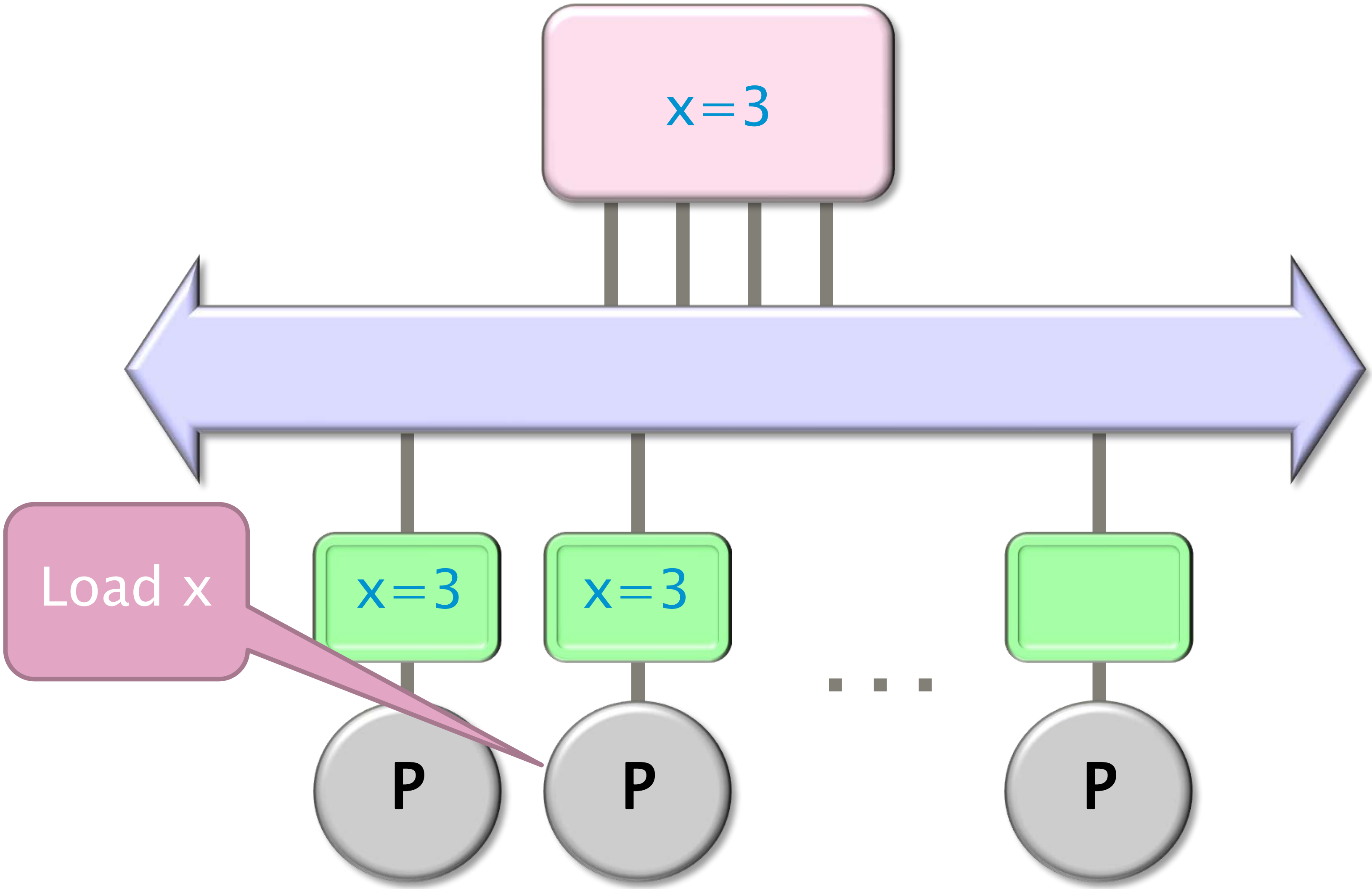

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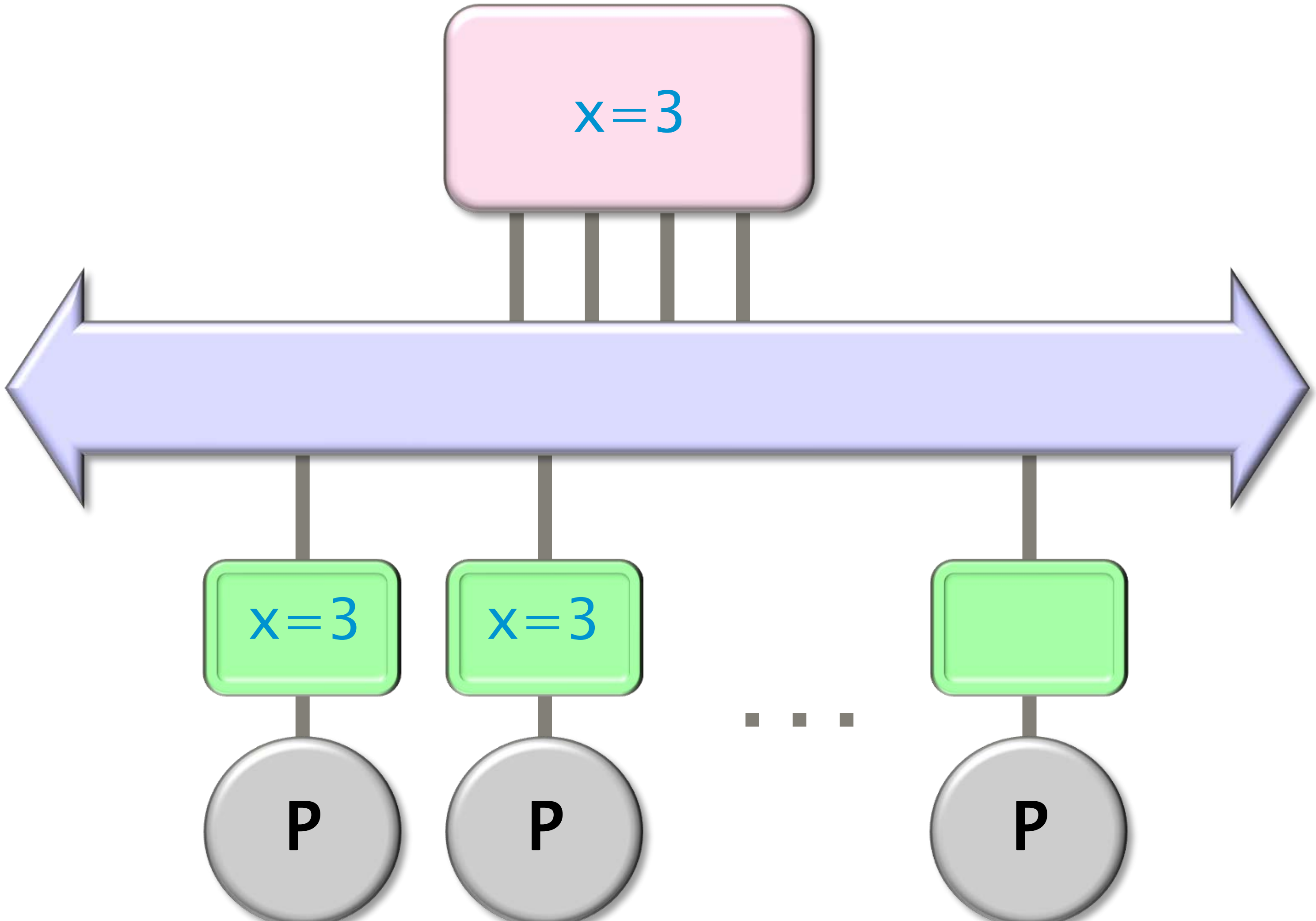

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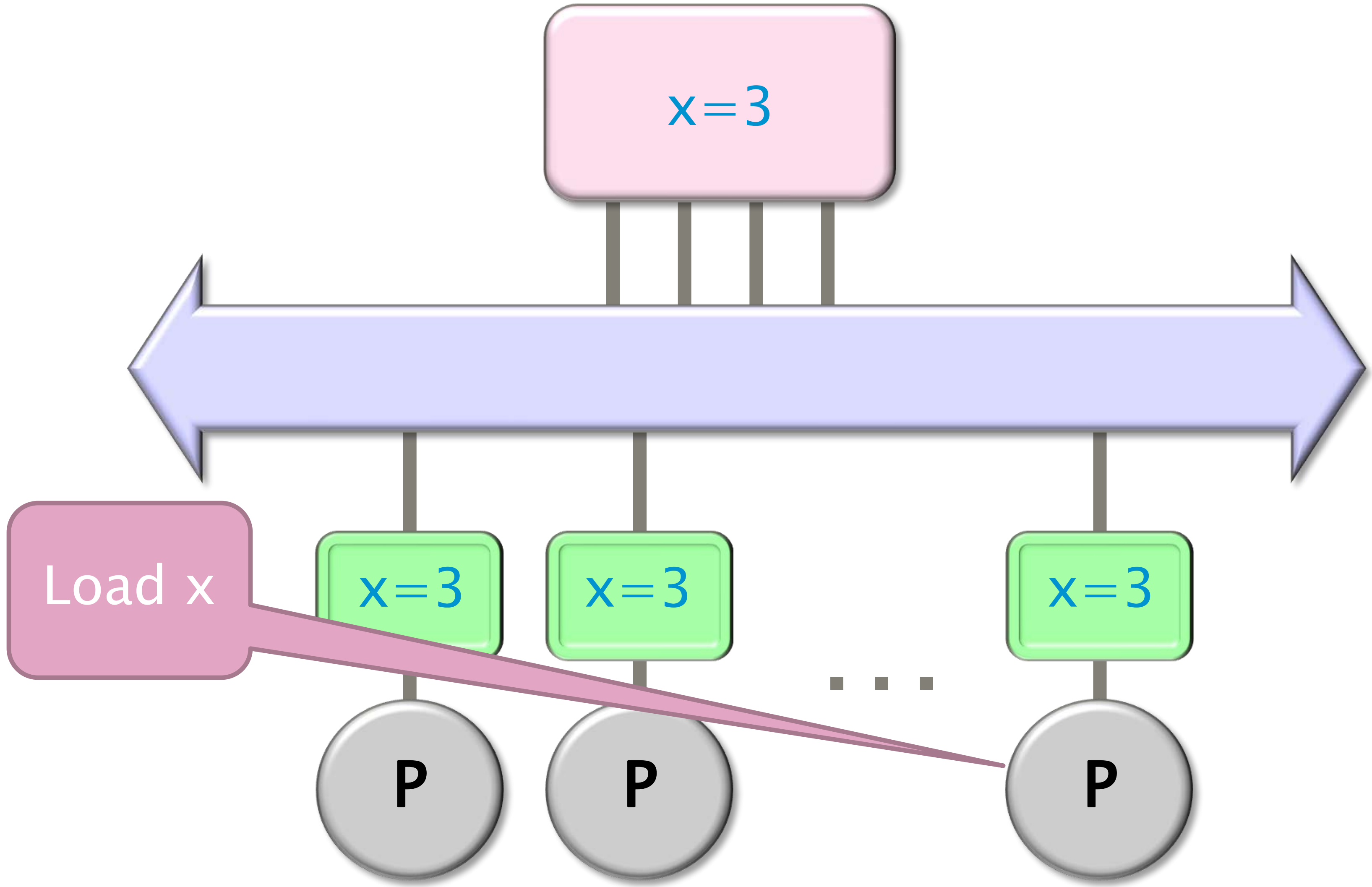

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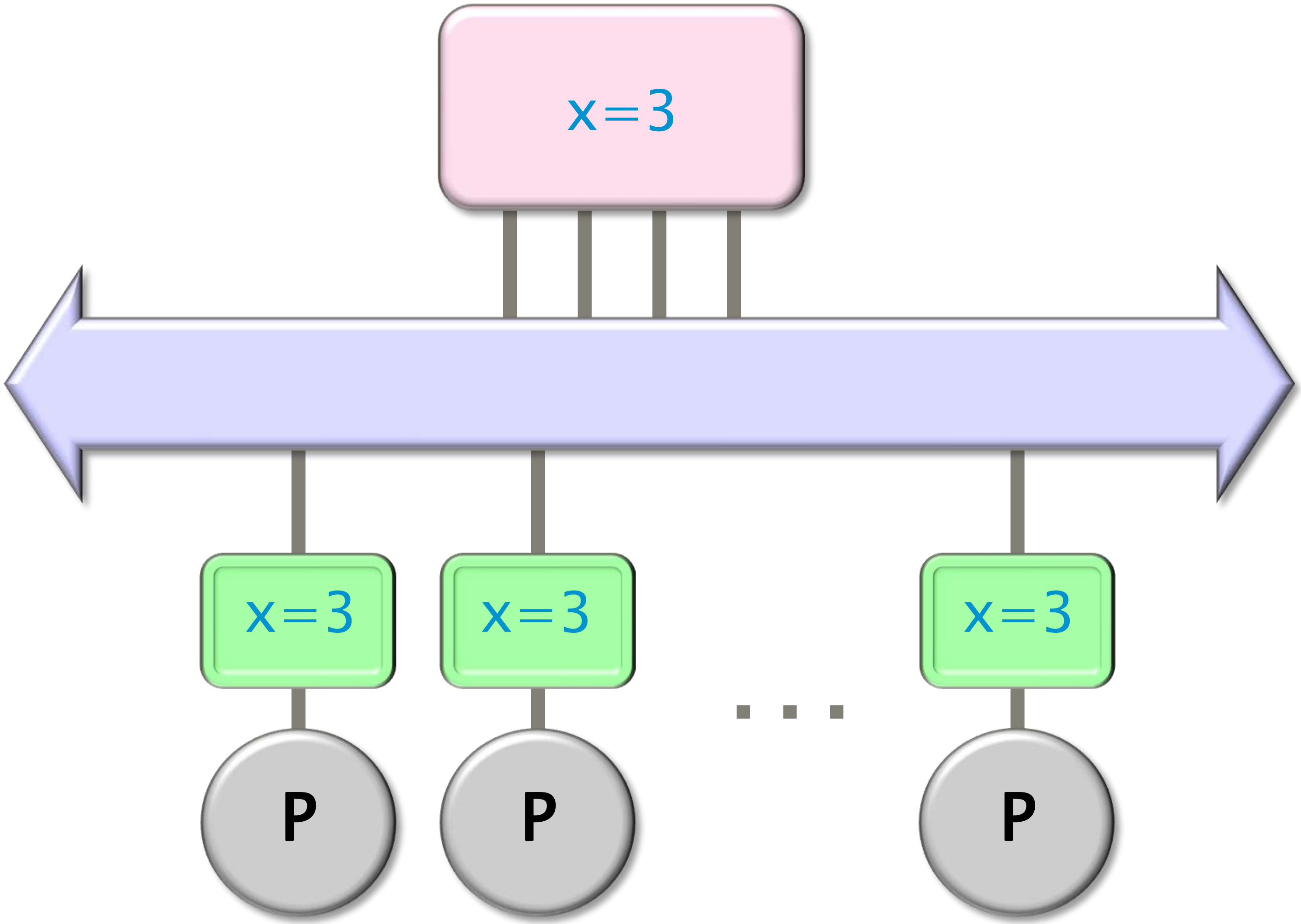
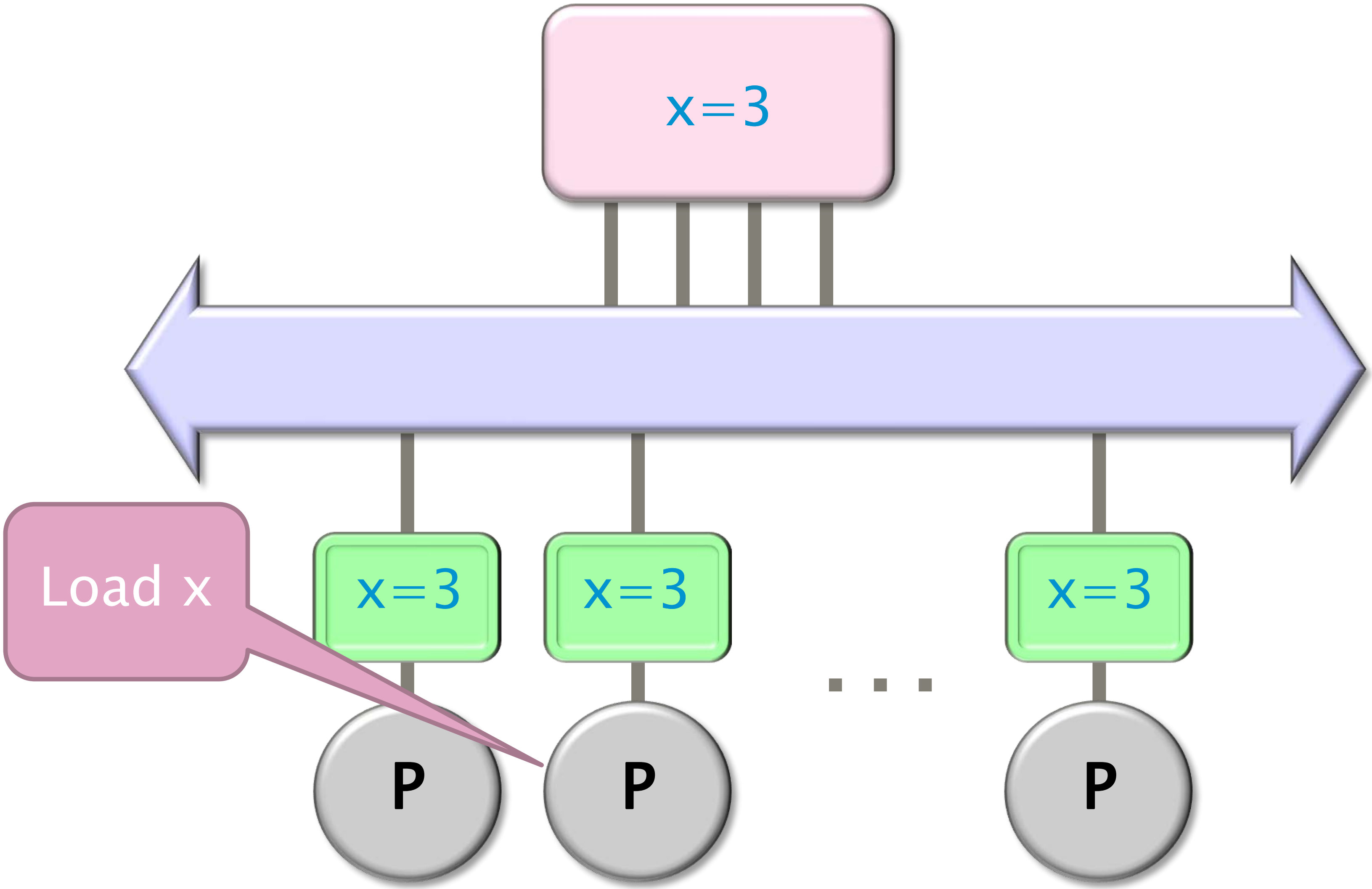


Cache Coherence



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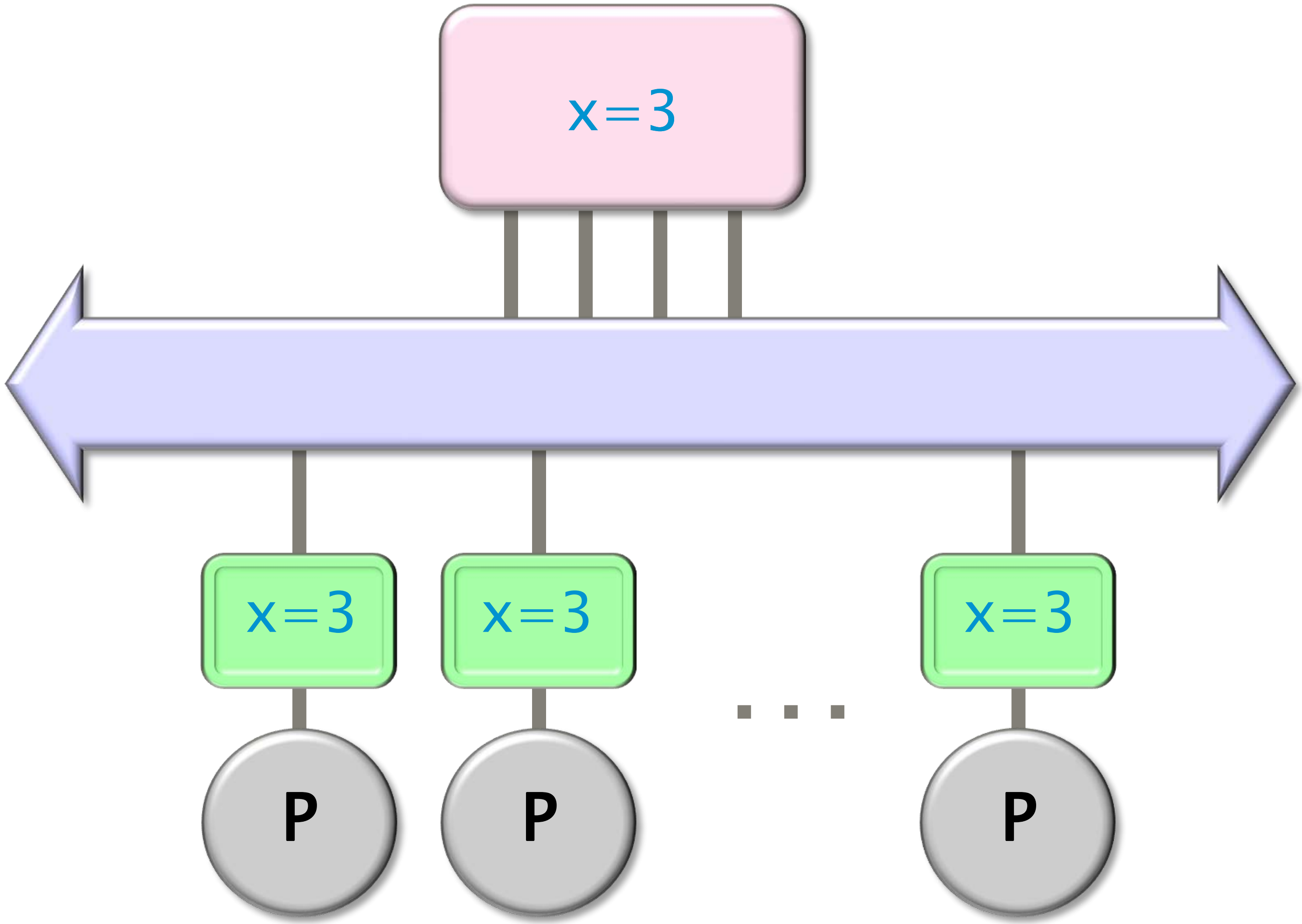
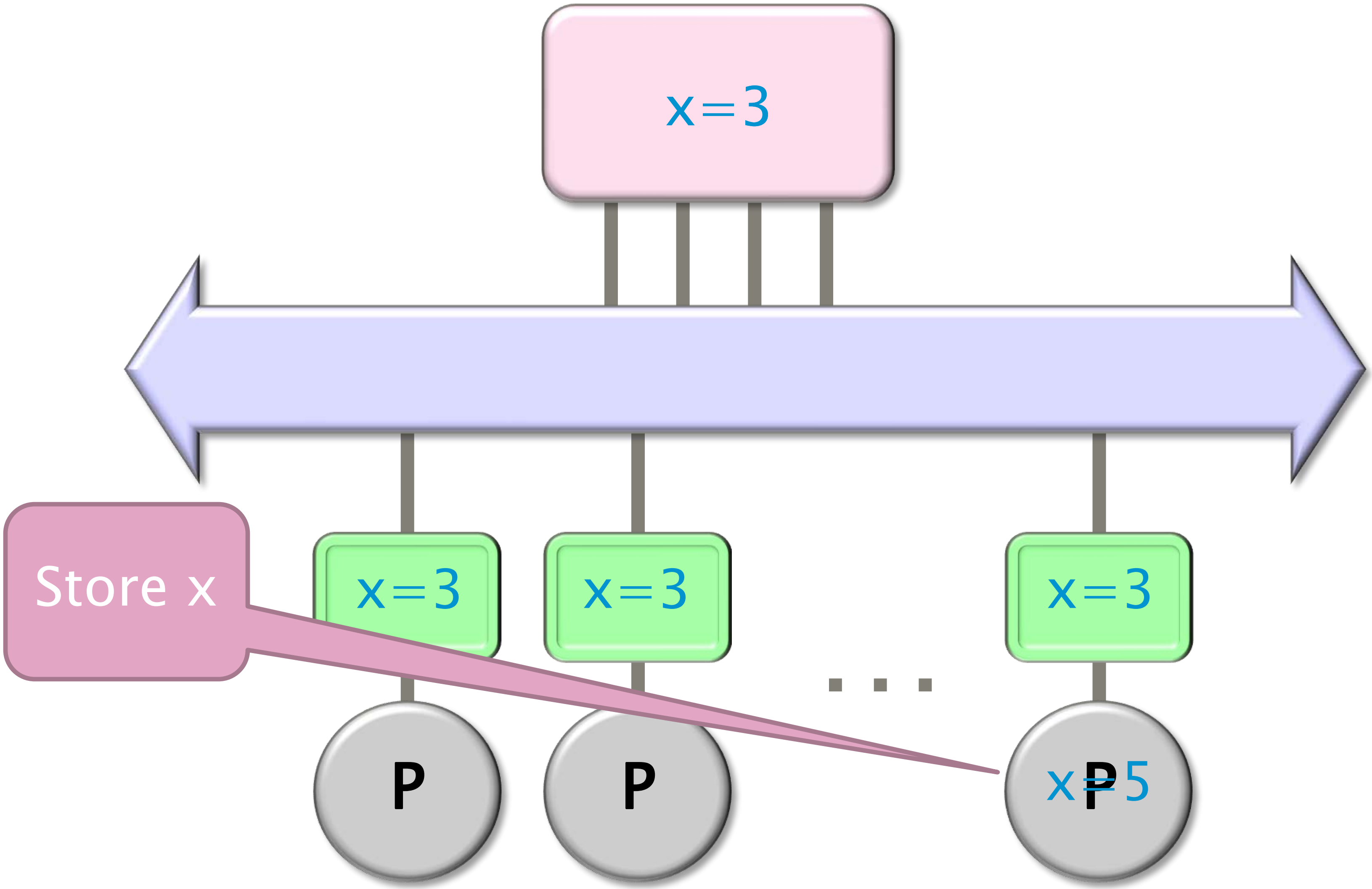
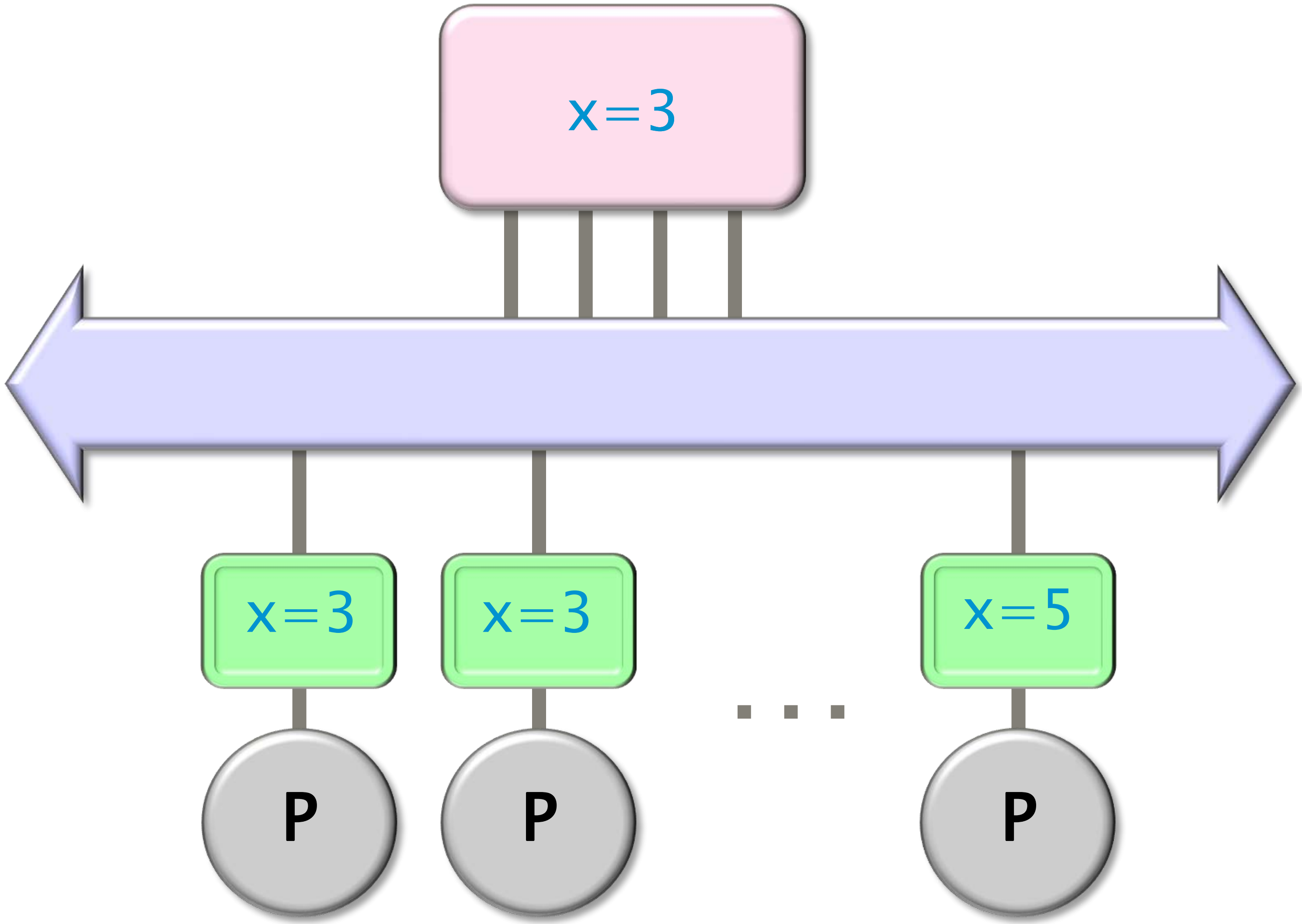


Cache Coherence



Cache Coherence



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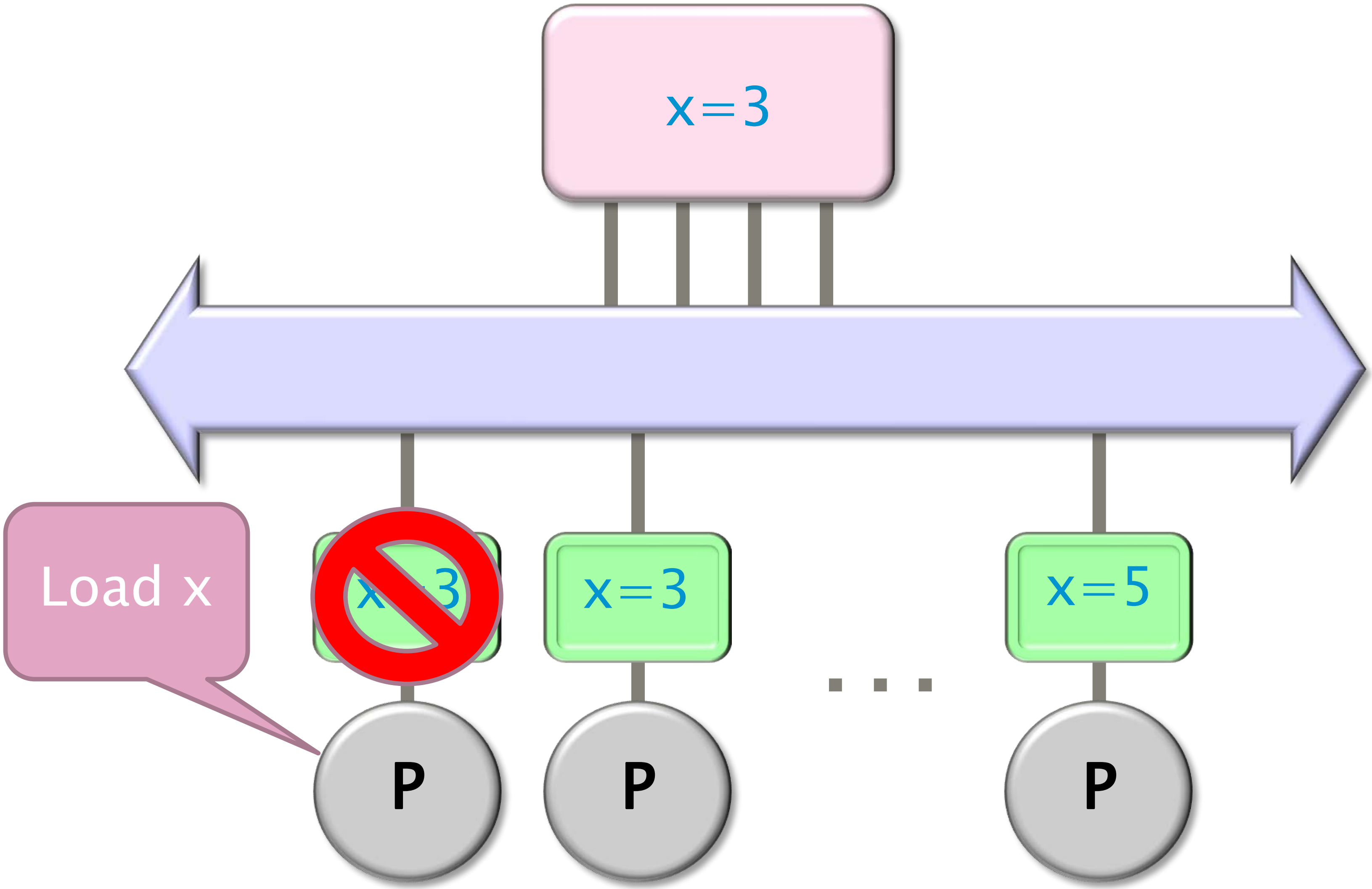


MSI Protocol

Each cache line is labeled with a state:

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

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	

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

OUTLINE

- Shared-Memory Hardware
- Concurrency Platforms
  - Pthreads (and WinAPI Threads)
  - Threading Building Blocks
  - OpenMP
  - Cilk++
- Race Conditions

Concurrency Platforms

- Programming directly on processor cores is painful and error-prone.
- A *concurrency platform* abstracts processor cores, handles synchronization and communication protocols, and performs load balancing.
- **Examples**
  - Pthreads and WinAPI threads
  - Threading Building Blocks (TBB)
  - OpenMP
  - Cilk++

Fibonacci Numbers

The *Fibonacci numbers* are the sequence ⟨0, 1, 1, 2, 3, 5, 8, 13, 21, 34, …⟩, 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.

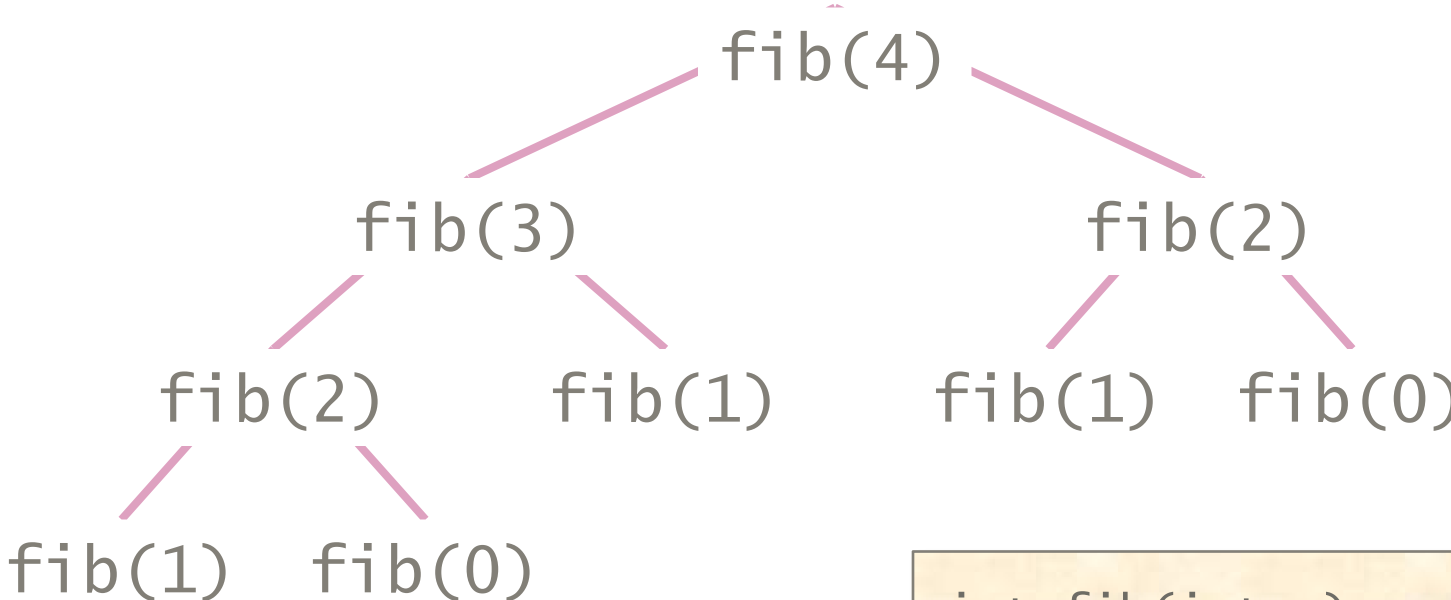
Fibonacci Program

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

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

int main(int argc, char *argv[])
{
  int n = atoi(argv[1]);
  int result = fib(n);
  printf("Fibonacci of %d is %d.\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

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

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

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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 though shared memory.
- Library functions mask the protocols involved in interthread 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
```

Pthread Implementation

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

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

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

void *thread_func ( void *ptr )
{
  int 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;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  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 %d is %d.\n", n, result);
  return 0;
}
```

Pthread Implementation

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

int fib(int n)
{
  if (n < 2) return n;
  else {
    int x = fib(n-1);
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typedef struct {
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void *thread_func ( void *ptr )
{
  int i = ((thread_args *) ptr)->input;
  ((thread_args *) ptr)->output = fib(i);
  return NULL;
}
```

Original code.

```c
int main(int argc, char *argv[])
{
  pthread_t thread;
  thread_args args;
  int status;
  int result;
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  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  if (n < 30) result = fib(n);
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    args.input = n-1;
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    // 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 %d is %d.\n", n, result);
  return 0;
}
```

Pthread Implementation

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#include <stdlib.h>
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void *thread_func ( void *ptr )
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  int i = ((thread_args *) ptr)->input;
  ((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;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  if (n < 30) result = fib(n);
  else {
    args.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 %d is %d.\n", n, result);
  return 0;
}
```

Pthread Implementation

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

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

Function called when thread is created.

```c
int main(int argc, char *argv[])
{
  pthread_t thread;
  thread_args args;
  int status;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  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 %d is %d.\n", n, result);
  return 0;
}
```

Pthread Implementation

```
#include <stdio.h>
#include <stdli
#include <pthre

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

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

void *thread_func ( void *ptr )
{
  int 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.

```
int main(int argc, char *argv[])
{
  pthread_t thread;
  thread_args args;
  int status;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
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    if (status != NULL) return(1);
    result += args.output;
  }
  printf("Fibonacci of %d is %d.\n", n, result);
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}
```

Pthread Implementation

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#include <stdio.h>
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  return NULL;
}
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```c
int main(int argc, char *argv[])
{
  pthread_t thread;
  thread_args args;
  int status;
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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 %d is %d.\n", n, result);
  return 0;
}
```

Marshal input argument to thread.

Pthread Implementation

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

int fib(int n)
{
  if (n < 2) return n;
  else {
    int x = fib(n-1);
    int y = fib(n-2);
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int main(int argc, char *argv[])
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  int status;
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    // 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 %d is %d.\n", n, result);
  return 0;
}
```

Create thread to execute fib(n-1).

Pthread Implementation

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

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

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

void *thread_func (
{
  int i = ((thread_
  ((thread_args *) 
  return NULL;
}
```

Main program executes fib(n-2) in parallel.

```c
int main(int argc, char *argv[])
{
  pthread_t thread;
  thread_args args;
  int status;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  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 %d is %d.\n", n, result);
  return 0;
}
```

Pthread Implementation

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

int fib(int n)
{
  if (n < 2) return n;
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    return x + y;
  }
}

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

void *thread_func
{
  int i = ((threac
  ((thread_args *)
  return NULL;
}
```

Block until the auxiliary thread finishes.

```c
int main(int argc, char *argv[])
{
  pthread_t thread;
  thread_args args;
  int status;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  if (n < 30) result = fib(n);
  else {
    args.input = n-1;
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                            NULL,
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    // 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 %d is %d.\n", n, result);
  return 0;
}
```

Pthread Implementation

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

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

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

void *thread_func ( void *ptr )
{
  int 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;
  int result;
  int thread_result;
  if (argc < 2) return 1;
  int n = atoi(argv[1]);
  if (n < 30) result = fib(n);
  else {
    args.input = n-1;
    status = pthread_create(&thread,
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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 %d is %d.\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 $\Rightarrow$ coarse-grained concurrency. (Thread pools can help.)

Scalability Fibonacci code gets 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 1958!*) and engage in error-prone protocols in order to load-balance.

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Threading Building Blocks

- Developed by **Intel**.
- Implemented as a **C++ library** that runs on top of native threads.
- Programmer specifies **tasks** rather than **threads**.
- Tasks are automatically **load balanced** across the threads using **work-stealing**.
- Focus on **performance**.

Reinders, James. *Intel Threading Building Blocks: Outfitting C++ for Multi-Core Processor Parallelism*. O'Reilly, 2007.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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;
    }
};
```

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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).

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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 a and wait for both a and b to finish.

Fibonacci in TBB

```
class FibTask: public task {
public:
    const long n;
    long* const sum;
    FibTask( long n_, long* sum_ ) :
             n(n_), sum(sum_) {}

    task* execute() {
        if( n < 2 ) {
            *sum = n;
        } else {
            long 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;
    }
};
```

Add the results together to produce the final output.

Other TBB Features

- TBB provides many C++ templates to express common patterns simply, such as
  - `parallel_for` for loop parallelism,
  - `parallel_reduce` for data aggregation,
  - `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.

OUTLINE

- Shared-Memory Hardware
- Concurrency Platforms
  - Pthreads (and WinAPI Threads)
  - Threading Building Blocks
  - OpenMP
  - Cilk++
- Race Conditions

OpenMP

- Specification produced by an industry consortium.
- Several compilers available, both open-source and proprietary, including gcc and Visual Studio.
- Linguistic extensions to C/C++ or Fortran in the form of compiler pragmas.
- Runs on top of native threads.
- Supports loop parallelism and, more recently in Version 3.0, task parallelism.

Fibonacci in OpenMP 3.0

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

Fibonacci in OpenMP 3.0

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

Compiler directive.

Fibonacci in OpenMP 3.0

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

The following statement is an independent task.

Fibonacci in OpenMP 3.0

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

Sharing of memory is managed explicitly.

Fibonacci in OpenMP 3.0

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

Wait for the two tasks to complete before continuing.

Other OpenMP Features

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

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Cilk++

- Small set of linguistic extensions to C++ to support fork-join parallelism.
- Developed by Cilk Arts, an MIT spin-off, which was acquired by Intel in July 2009.
- Based on the award-winning Cilk multithreaded language developed at MIT.
- Features a provably efficient work-stealing scheduler.
- Provides a hyperobject library for parallelizing code with global variables.
- Includes the Cilkscreen race detector and Cilkview scalability analyzer.

Nested Parallelism in Cilk++

```
int fib(int n)
{
   if (n < 2) return n
   int x, y;
   x = cilk_spawn fib(n-1);
   y = fib(n-2);
   cilk_sync;
   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.

Cilk++ keywords *grant permission* for parallel execution. They do not *command* parallel execution.

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

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

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

C++ serialization

The C++ *serialization* 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 serialization:

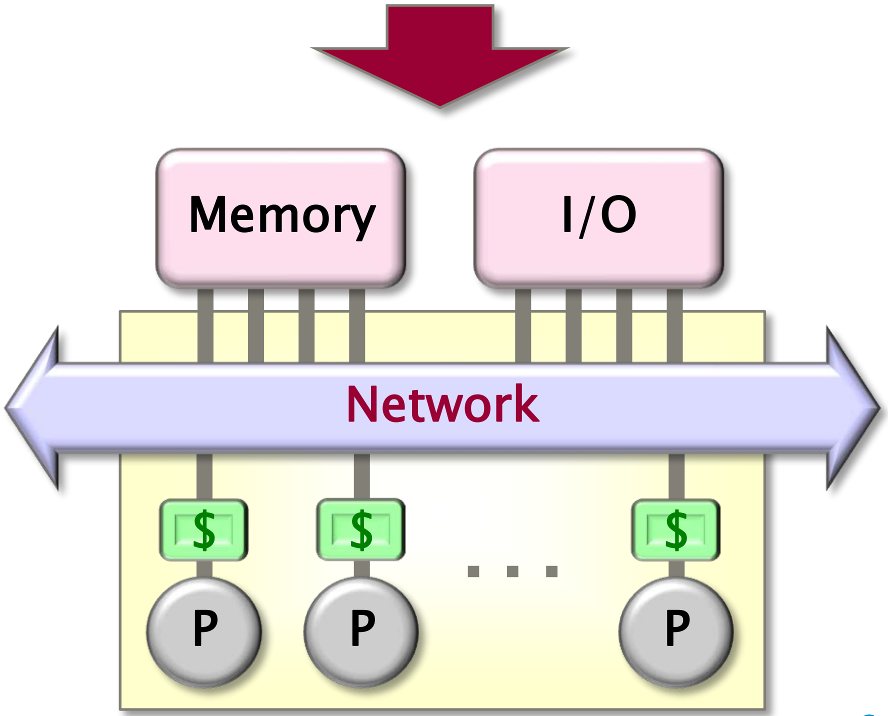
```
#define cilk_for for
#define cilk_spawn
#define cilk_sync
```

Or, specify a switch to the Cilk++ compiler.

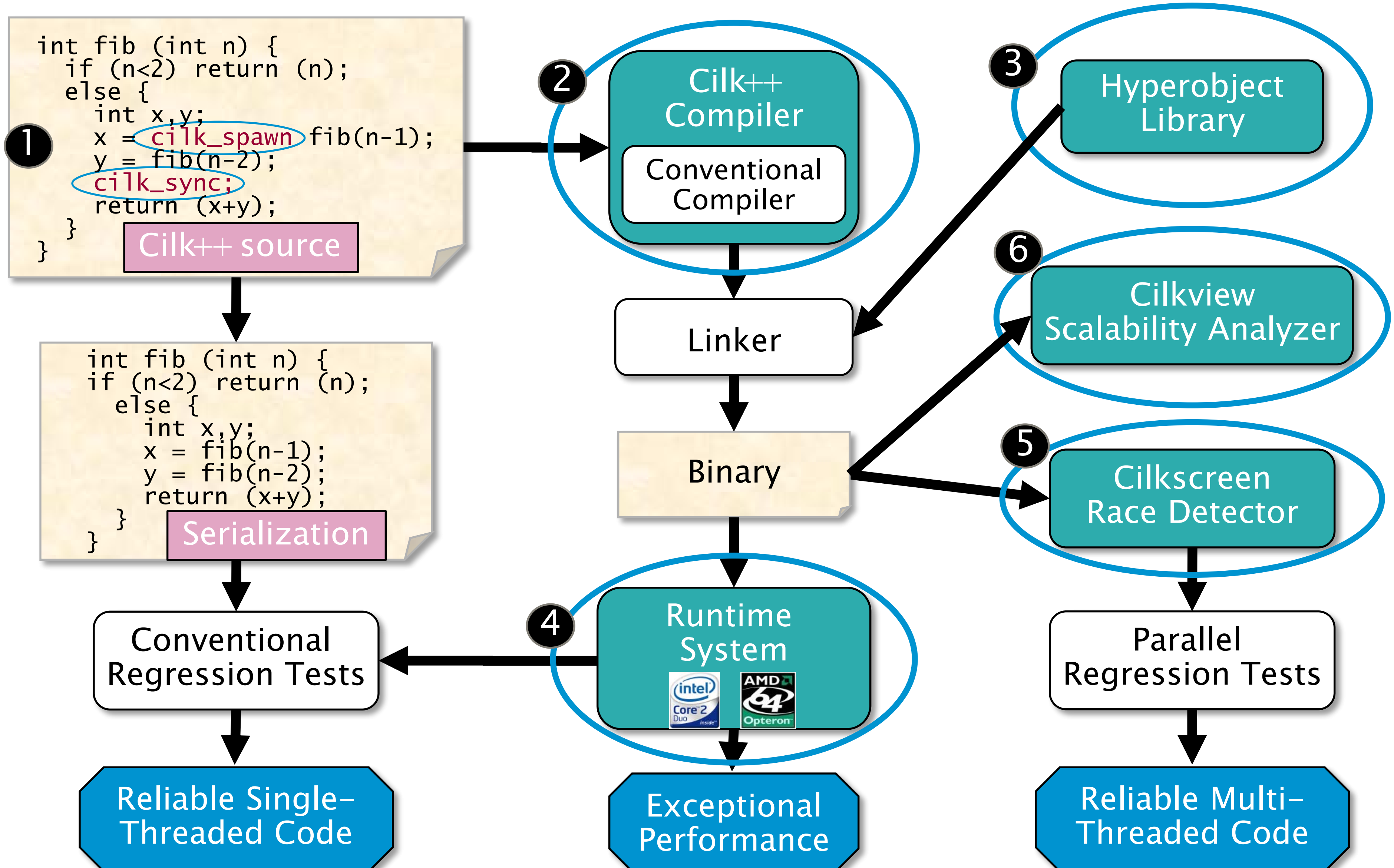
Scheduling

- The Cilk++ concurrency platform allows the programmer to express *potential* parallelism in an application.
- The Cilk++ *scheduler* maps the executing program onto the processor cores dynamically at runtime.
- Cilk++'s *work-stealing* scheduler is provably efficient.

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



Cilk++ Platform



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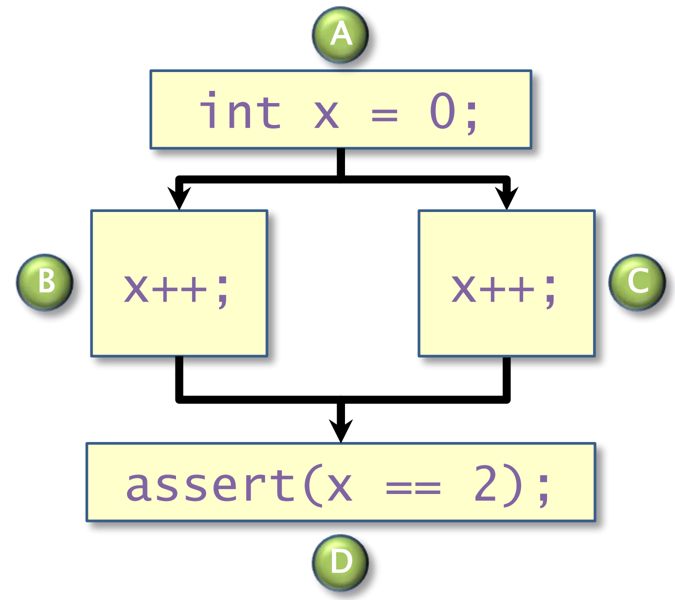
Determinacy Races

Definition. A *determinacy race* occurs when two logically parallel instructions access the same memory location and at least one of the instructions performs a write.

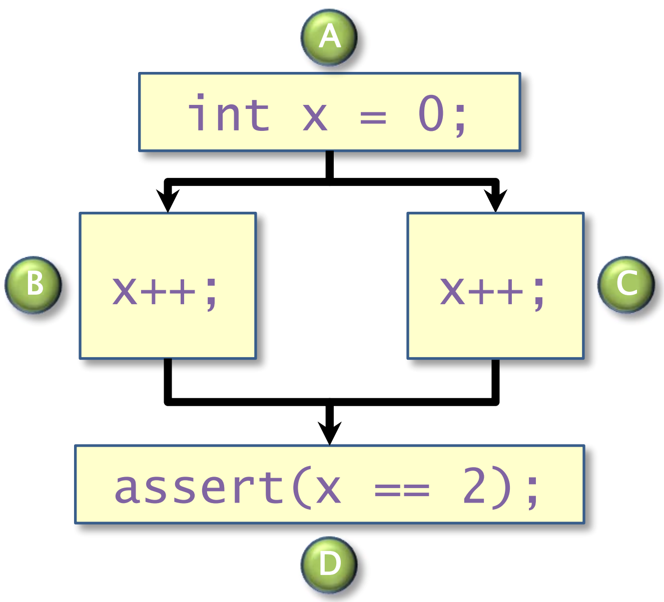
Example

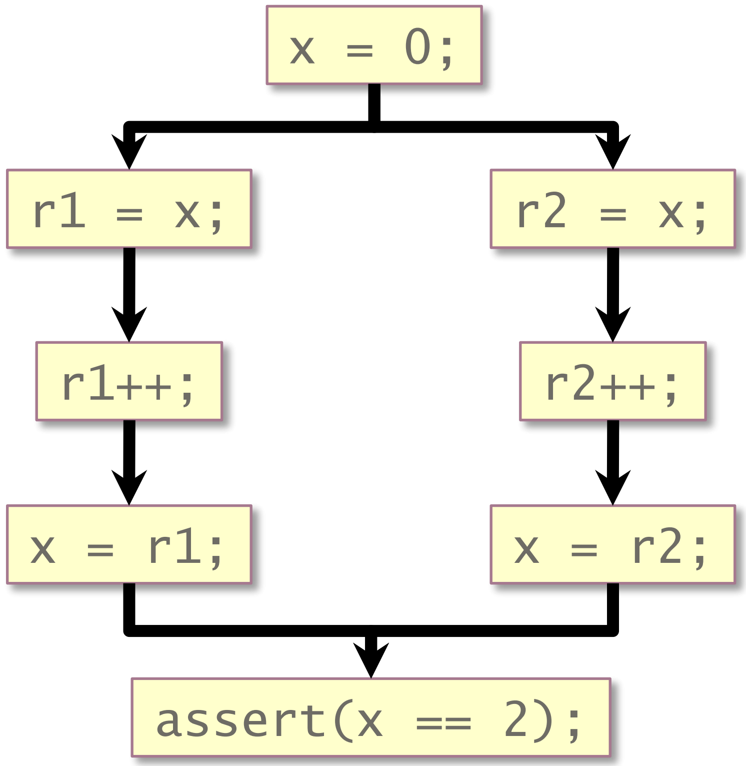
```
int x = 0;
cilk_for (int i=0, i<2, ++i) {
    x++;
}
assert(x == 2);
```



Dependency Graph

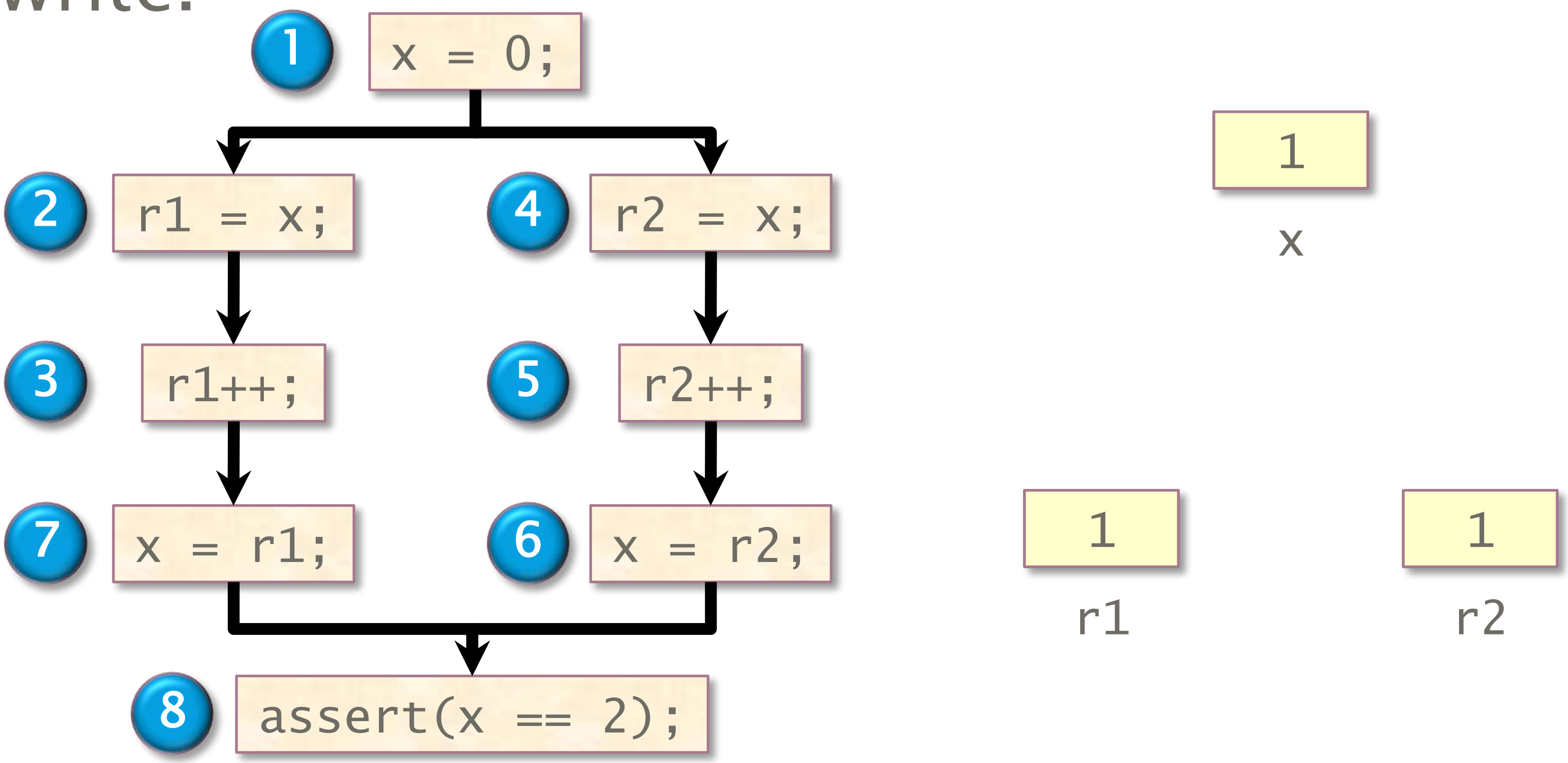
A Closer Look





Race Bugs

Definition. A *determinacy race* occurs when two logically parallel instructions access the same memory location and at least one of the instructions performs a write.



Types of Races

Suppose that instruction A and instruction B both access a location x, and suppose that A∥B (A is parallel to B).

A	B	Race Type
read	read	none
read	write	read race
write	read	read race
write	write	write race

Two sections of code are *independent* if they have no determinacy races between them.

Avoiding Races

- Iterations of a `cilk_for` should be independent.
- Between a `cilk_spawn` and the corresponding `cilk_sync`, the code of the spawned child should be independent of the code of the parent, including code executed by additional spawned or called children.
  Note: The arguments to a spawned function are evaluated in the parent before the spawn occurs.
- Machine word size matters. Watch out for races in packed data structures:

```
struct{
    char a;
    char b;
} x;
```

Ex. Updating `x.a` and `x.b` in parallel may cause a race! Nasty, because it may depend on the compiler optimization level. (Safe on Intel.)

Cilkscreen Race Detector

- If an ostensibly deterministic Cilk++ program run on a given input could possibly behave any differently than its serialization, Cilkscreen **guarantees** to report and localize the offending race.
- Employs a **regression-test** methodology, where the programmer provides test inputs.
- **Identifies** filenames, lines, and variables involved in races, including stack traces.
- Runs off the binary executable using **dynamic instrumentation**.
- Runs about **20** times slower than real-time.

6.172 Performance Engineering of Software Systems
Fall 2010