6.172
Performance
Engineering
of Software
Systems

LECTURE 16
NONDETERMINISTIC PARALLEL PROGRAMMING

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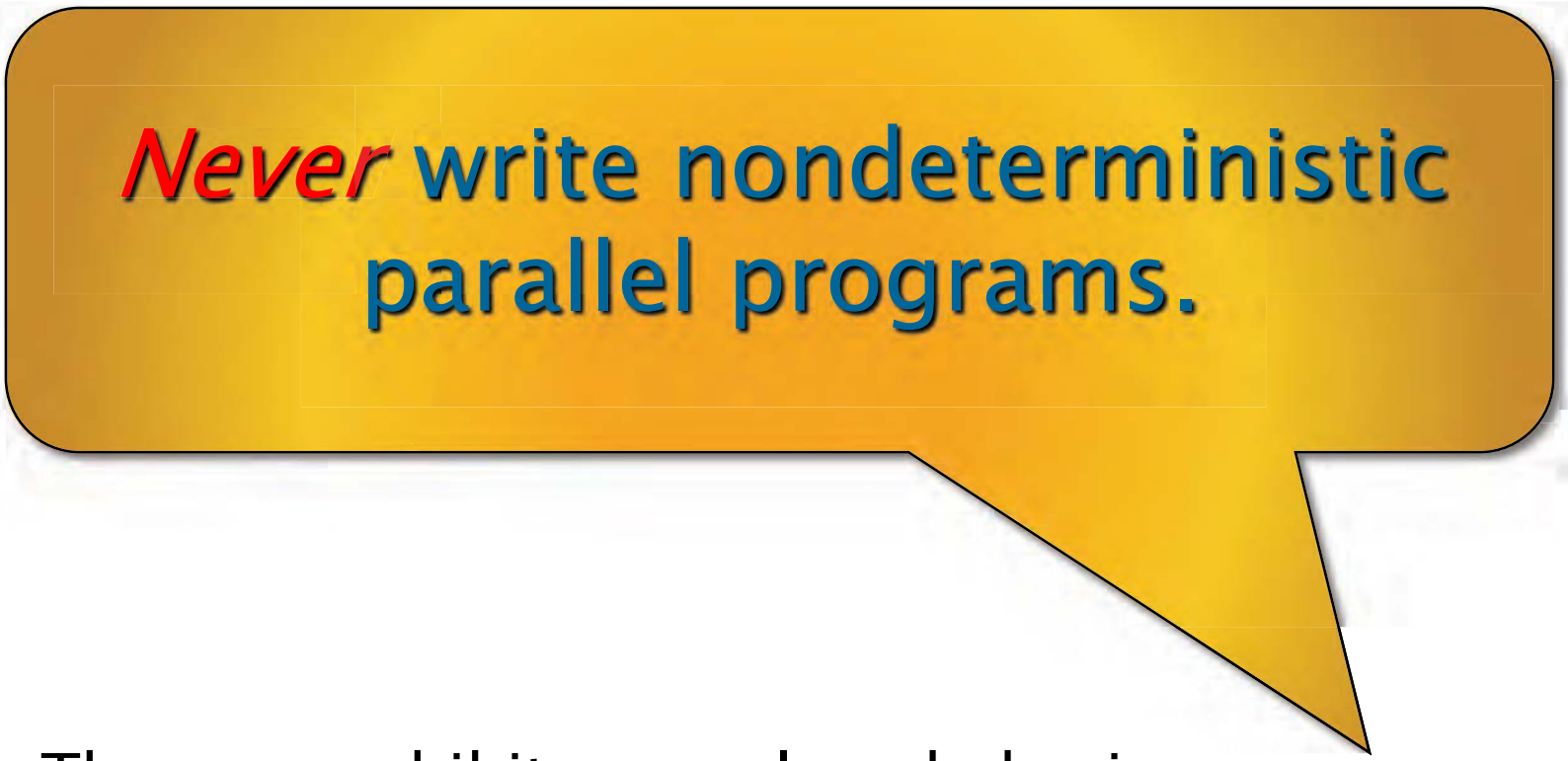
Determinism

Definition. A program is *deterministic* on a given input if every memory location is updated with the same sequence of values in every execution.

- The program always behaves the same way.
- Two different memory locations may be updated in different orders, but each location always sees the same sequence of updates.

Advantage: DEBUGGING!

Golden Rule of Parallel Programming



They can exhibit anomalous behaviors, and it's hard to debug them.

Silver Rule of Parallel Programming

Never write nondeterministic parallel programs

— but if you must —*

always devise a test strategy to manage the nondeterminism!

Typical test strategies

- Turn off nondeterminism.
- Encapsulate nondeterminism.
- Substitute a deterministic alternative.
- Use analysis tools.

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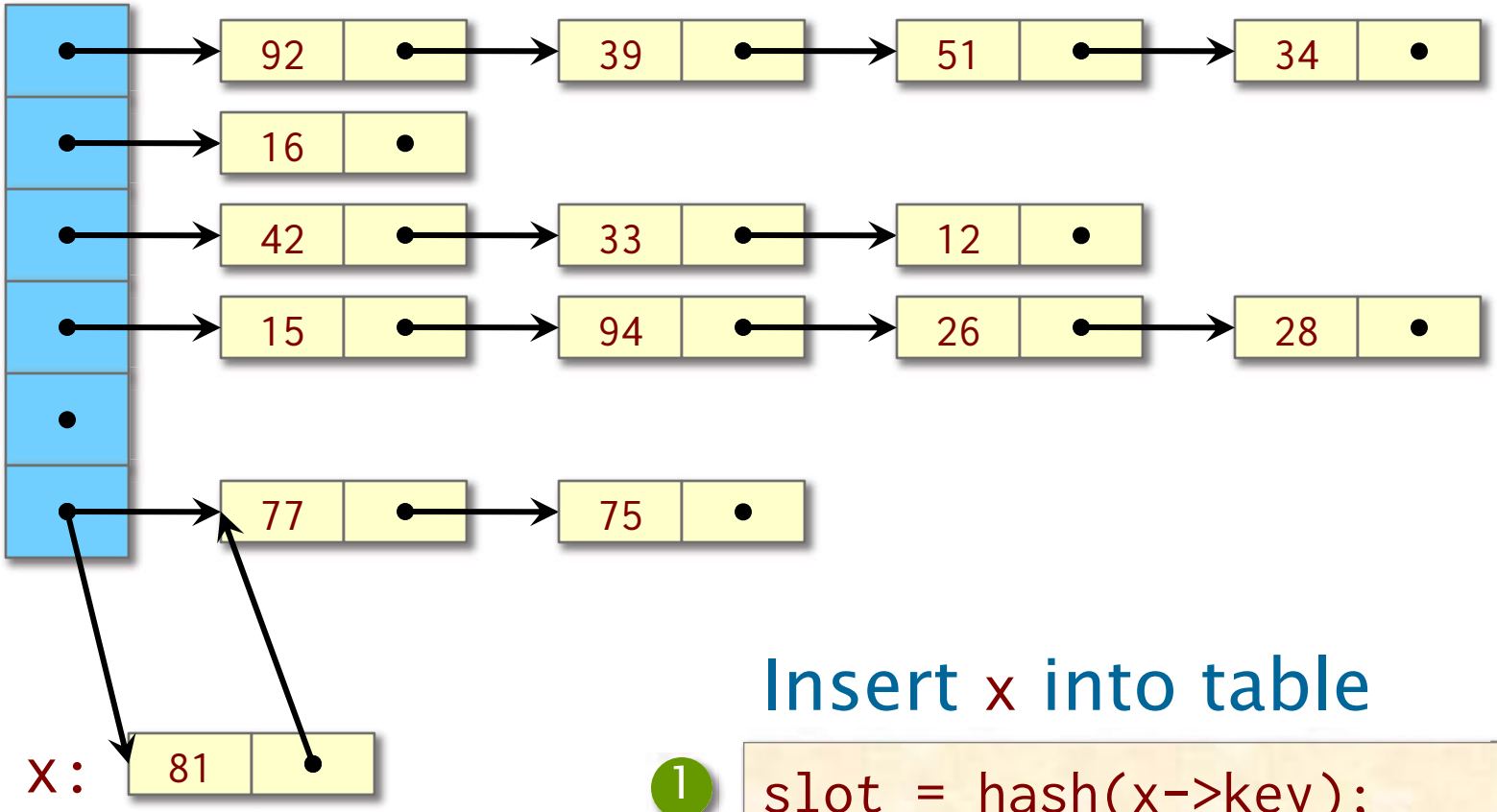
*E.g., for performance reasons.

Mutual Exclusion & Atomicity

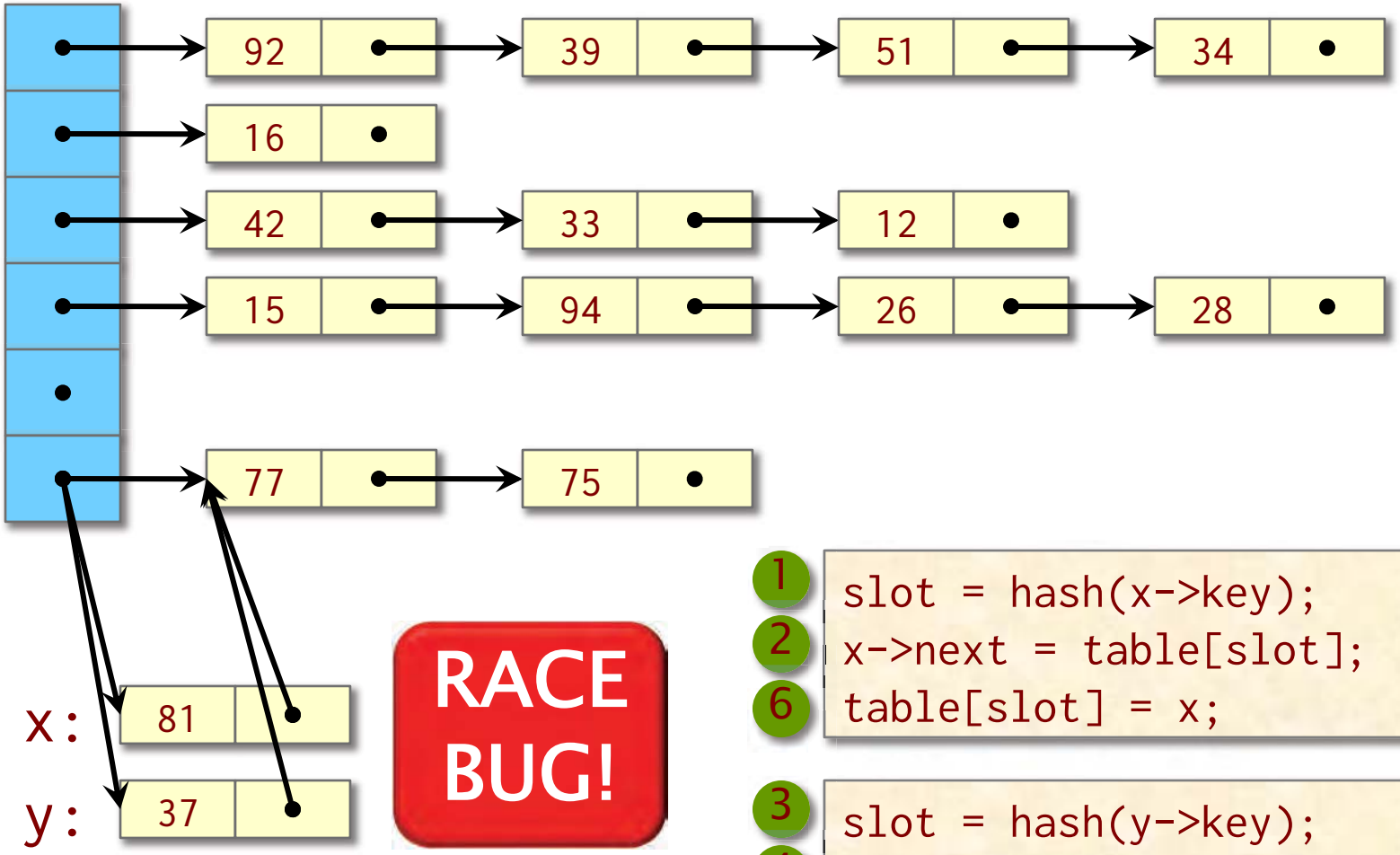
Hash Table



Insert x into table

```
1  slot = hash(x->key);
2  x->next = table[slot];
3  table[slot] = x;
```

Concurrent Hash Table



Atomicity

Definition. A sequence of instructions is *atomic* if the rest of the system cannot ever view them as partially executed. At any moment, either no instructions in the sequence have executed or all have executed.

Definition. A *critical section* is a piece of code that accesses a shared data structure that must not be accessed by two or more threads at the same time (*mutual exclusion*).

Mutexes

Definition. A *mutex* is an object with `lock` and `unlock` member functions. An attempt by a thread to lock an already locked mutex causes that thread to *block* (*i.e.*, wait) until the mutex is unlocked.

Modified code: Each slot is a `struct` with a mutex `L` and a pointer `head` to the slot contents.

critical section

```
slot = hash(x->key);
lock(&table[slot].L);
  x->next = table[slot].head;
  table[slot].head = x;
unlock(&table[slot].L);
```

Mutexes can be used to implement atomicity.

Recall: 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.

- A program execution with no determinacy races means that the program is deterministic on that input.
- The program always behaves the same on that input, no matter how it is scheduled and executed.
- If determinacy races exist in an ostensibly deterministic program (e.g., a program with no mutexes), Cilksan guarantees to find such a race.

Data Races

Definition. A *data race* occurs when two logically parallel instructions *holding no locks in common* access the same memory location and at least one of the instructions performs a write.

Although data-race-free programs obey atomicity constraints, they can still be nondeterministic, because acquiring a lock can cause a determinacy race with another lock acquisition.

WARNING: Codes that use locks are nondeterministic by intention, and they invalidate Cilksan's guarantee.

No Data Races ≠ No Bugs

Example

```
slot = hash(x->key);

lock(&table[slot].L);
  x->next = table[slot].head;
unlock(&table[slot].L);

lock(&table[slot].L);
  table[slot].head = x;
unlock(&table[slot].L);
```

Nevertheless, the presence of mutexes and the absence of data races at least means that the programmer thought about the issue.

"Benign" Races

Example: Identify the set of digits in an array.

A: 4, 1, 0, 4, 3, 3, 4, 6, 1, 9, 1, 9, 6, 6, 6, 3, 4

```
for (int i=0; i<10; ++i) {
    digits[i] = 0;
}
cilk_for (int i=0; i<N; ++i) {
    digits[A[i]] = 1;  //benign race
}
```

digits:

1	1	0	1	1	1	1	0	0	1
0	1	2	3	4	5	6	7	8	9

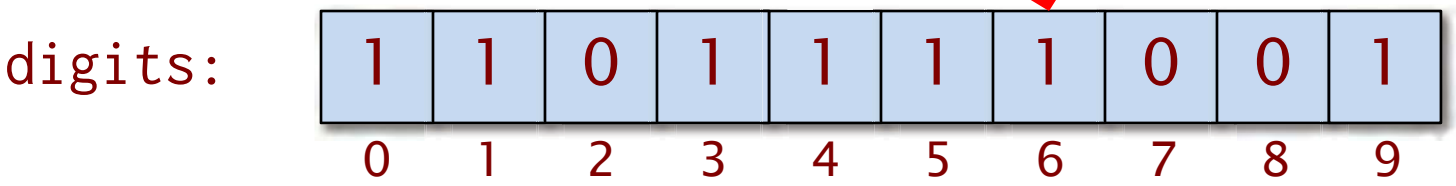
CAUTION: This code only works correctly if the hardware writes the array elements atomically — e.g., it races for byte values on some architectures.

"Benign" Races

Example: Identify the set of digits in an array.

A: 4, 1, 0, 4, 3, 3, 4, 6, 1, 9, 1, 9, 6, 6, 6, 3, 4

```
for (int i=0; i<10; ++i) {
    digits[i] = 0;
}
cilk_for (int i=0; i<N; ++i) {
    digits[A[i]] = 1;  //benign race
}
```



Cilksan allows you to turn off race detection for intentional races, which is dangerous but practical. Better solutions exist, e.g., *fake locks* in Intel's Cilkscreen (See Intel Cilk Plus Tools User's Guide.)

Implementation of Mutexes

Properties of Mutexes

- **Yielding/spinning**
  A yielding mutex returns control to the operating system when it blocks. A spinning mutex consumes processor cycles while blocked.
- **Reentrant/nonreentrant**
  A reentrant mutex allows a thread that is already holding a lock to acquire it again. A nonreentrant mutex deadlocks if the thread attempts to reacquire a mutex it already holds.
- **Fair/unfair**
  A fair mutex puts blocked threads on a FIFO queue, and the unlock operation unblocks the thread that has been waiting the longest. An unfair mutex lets any blocked thread go next.

Simple Spinning Mutex

```
Spin_Mutex:
        cmp 0, mutex ; Check if mutex is free
        je Get_Mutex
        pause ; x86 hack to unconfuse pipeline
        jmp Spin_Mutex
Get_Mutex:
        mov 1, %eax
        xchg mutex, %eax ; Try to get mutex
        cmp 0, %eax ; Test if successful
        jne Spin_Mutex
Critical_Section:
        <critical-section code>
        mov 0, mutex ; Release mutex
```

Key property: `xchg` is an atomic exchange.

Simple Yielding Mutex

```
Spin_Mutex:
        cmp 0, mutex ; Check if mutex is free
        je Get_Mutex
        call pthread_yield ; Yield quantum
        jmp Spin_Mutex
Get_Mutex:
        mov 1, %eax
        xchg mutex, %eax ; Try to get mutex
        cmp 0, %eax ; Test if successful
        jne Spin_Mutex
Critical_Section:
        <critical-section code>
        mov 0, mutex ; Release mutex
```

Competitive Mutex

Competing goals:

- To claim mutex soon after it is released.
- To behave nicely and waste few cycles.

IDEA: Spin for a while, and then yield.

How long to spin?

As long as a context switch takes. Then, you never wait longer than twice the optimal time.

- If the mutex is released while spinning, optimal.
- If the mutex is released after yield, $\leq 2 \times$ optimal.

Randomized algorithm [KMMO94]

A clever randomized algorithm can achieve a competitive ratio of $e/(e-1) \approx 1.58$.

Locking Anomaly: Deadlock

Deadlock

Holding more than one lock at a time can be dangerous:

Thread 1

1
```
lock(&A);
lock(&B);
  ⟨critical section⟩
unlock(&B);
unlock(&A);
```

Thread 2

2
```
lock(&B);
lock(&A);
  ⟨critical section⟩
unlock(&A);
unlock(&B);
```

The ultimate loss of performance!

Conditions for Deadlock

1. **Mutual exclusion** — Each thread claims exclusive control over the resources it holds.
2. **Nonpreemption** — Each thread does not release the resources it holds until it completes its use of them.
3. **Circular waiting** — A cycle of threads exists in which each thread is blocked waiting for resources held by the next thread in the cycle.

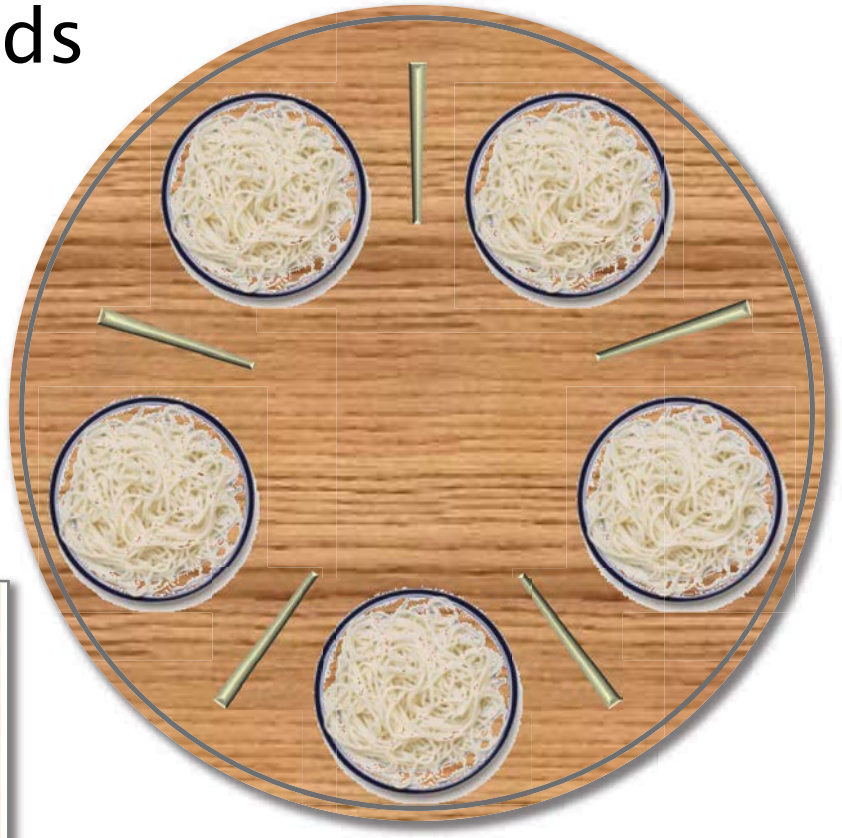
Dining Philosophers

C.A.R. (Tony) Hoare *Edsger Dijkstra*

Illustrative story of deadlock told by Charles Antony Richard Hoare based on an examination question by Edsgar Dijkstra. The story has been embellished over the years by many retellers.

Dining Philosophers

Each of n philosophers needs the two chopsticks on either side of his/her plate to eat his/her noodles.

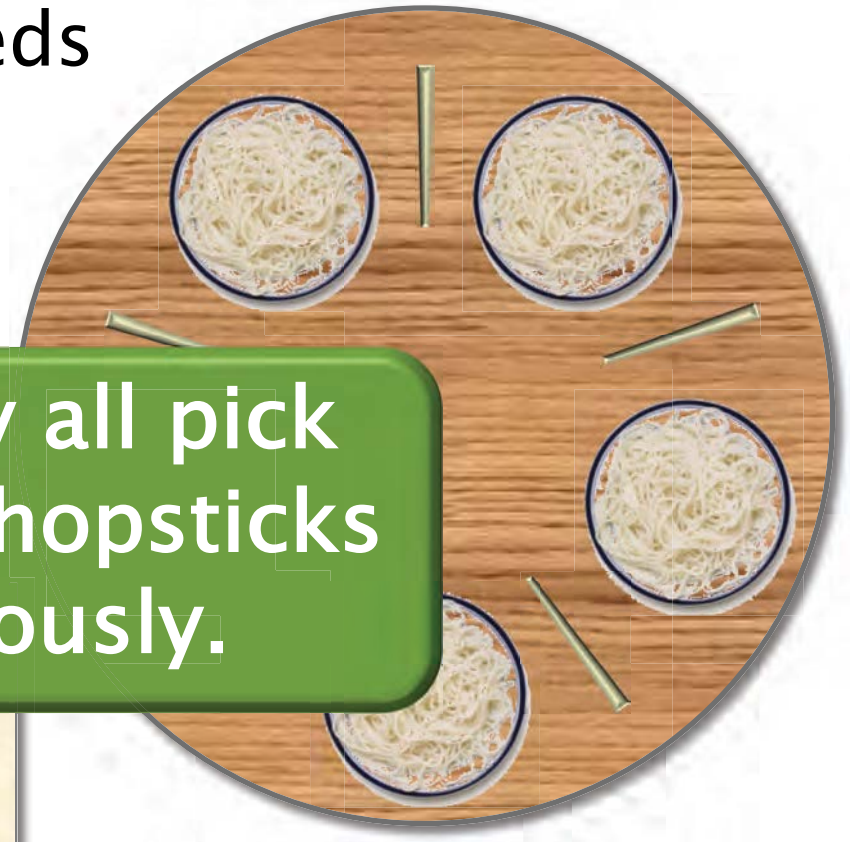


Philosopher i

```
while (1) {
  think();
  lock(&chopstick[i].L);
  lock(&chopstick[(i+1)%n].L);
    eat();
  unlock(&chopstick[i].L);
  unlock(&chopstick[(i+1)%n].L);
}
```

~~Dining~~ Philosophers Starving

Each of n philosophers needs the two chopsticks on either side of his/her plate to eat his/her noodles.



One day they all pick up their left chopsticks simultaneously.

Philosopher

```
while (1) {
  think();
  lock(&chopstick[i].L);
  lock(&chopstick[(i+1)%n].L);
    eat();
  unlock(&chopstick[i].L);
  unlock(&chopstick[(i+1)%n].L);
}
```

Preventing Deadlock

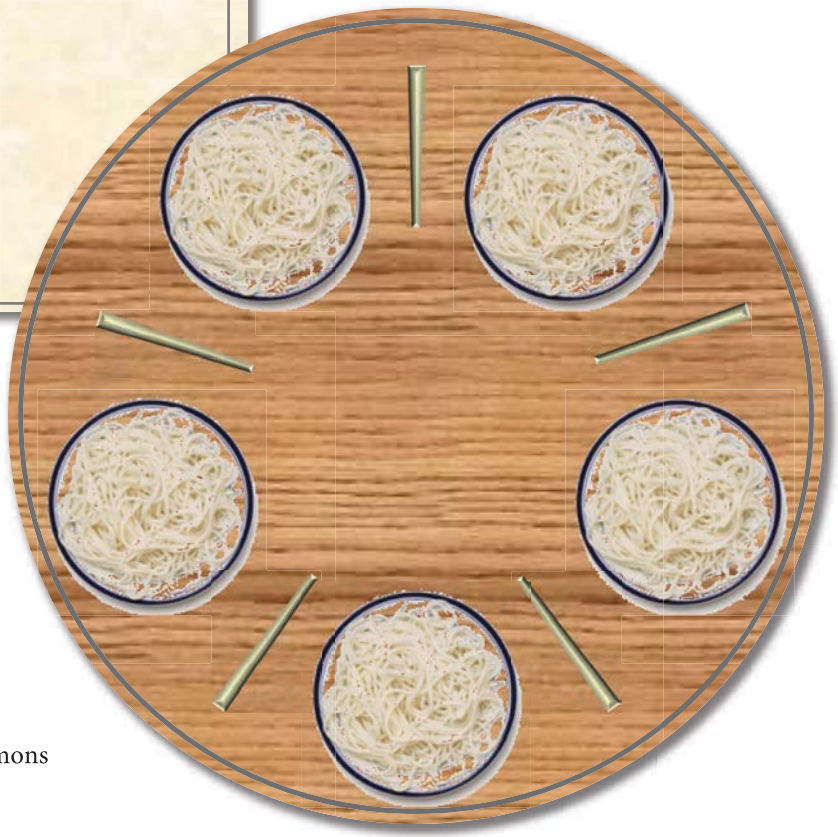
Theorem. Assume that we can linearly order the mutexes $L_1 \lessdot L_2 \lessdot \cdots \lessdot L_n$ so that whenever a thread holds a mutex L_i and attempts to lock another mutex L_j, we have $L_i \lessdot L_j$. Then, no deadlock can occur.

Proof. Suppose that a cycle of waiting exists. Consider the thread in the cycle that holds the "largest" mutex L_{max} in the ordering, and suppose that it is waiting on a mutex L held by the next thread in the cycle. Then, we must have $L_{max} \lessdot L$. Contradiction. ■

Dining Philosophers

Philosopher `i`

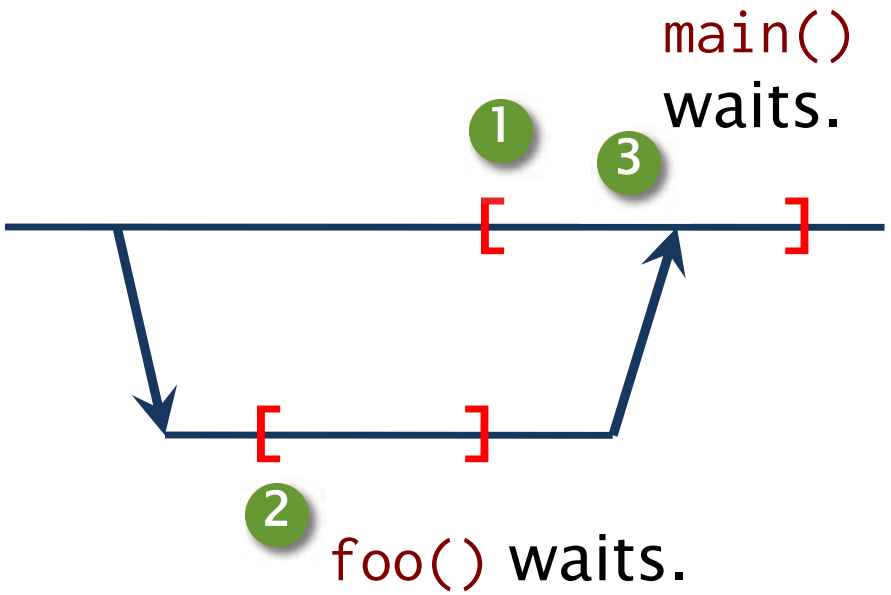
```
while (1) {
  think();
  lock(&chopstick[min(i,(i+1)%n)].L);
  lock(&chopstick[max(i,(i+1)%n)].L);
    eat();
  unlock(&chopstick[i].L);
  unlock(&chopstick[(i+1)%n].L);
}
```



Deadlocking Cilk

```
void main() {
  cilk_spawn foo();
  lock(&L);
  cilk_sync;
  unlock(&L);
}

void foo() {
  lock(&L);
  unlock(&L);
}
```

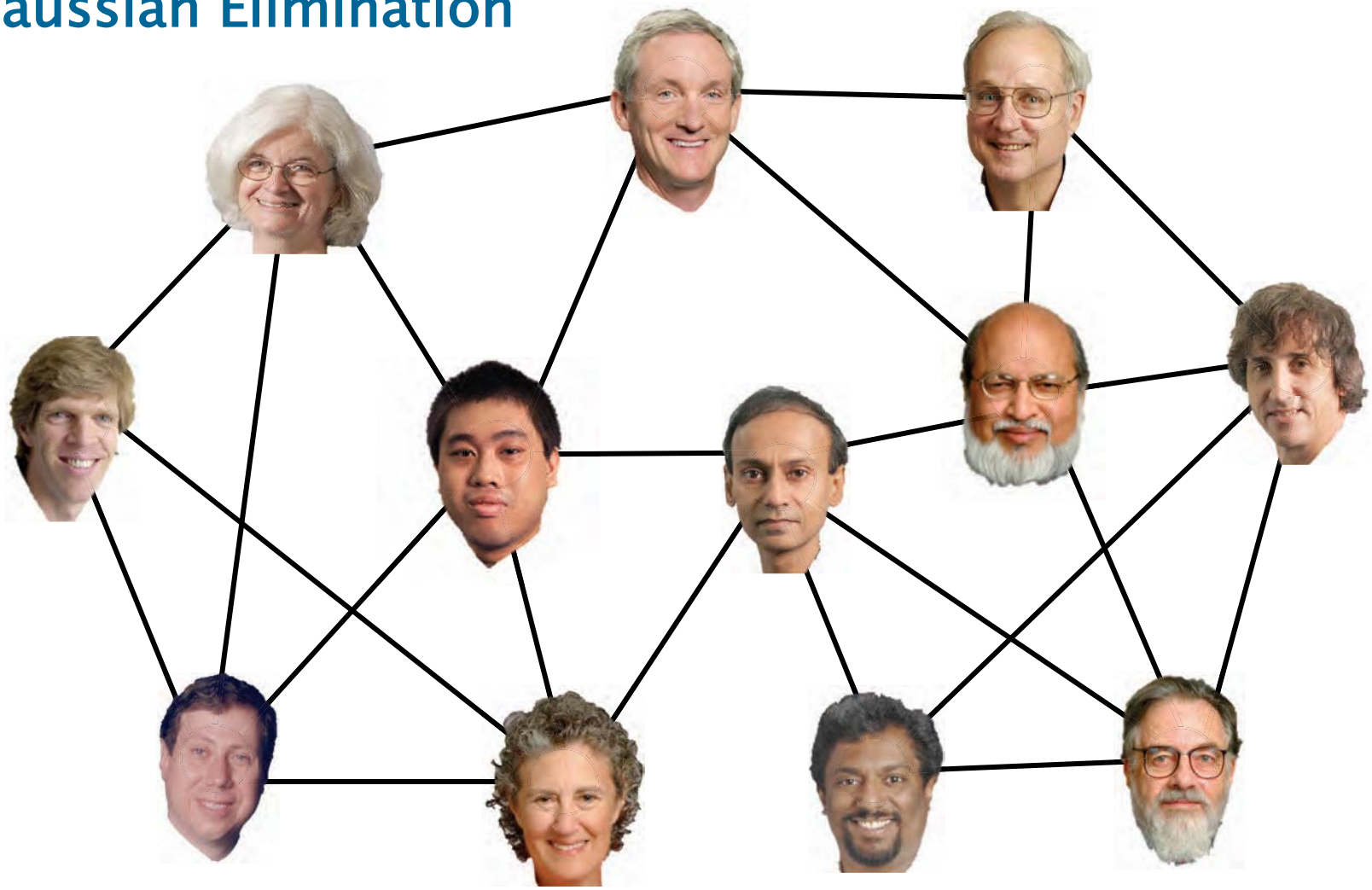


- Don't hold mutexes across `cilk_sync`'s!
- Hold mutexes only within strands.
- As always, try to avoid nondeterministic programming (but that's not always possible).

TRANSACTIONAL MEMORY

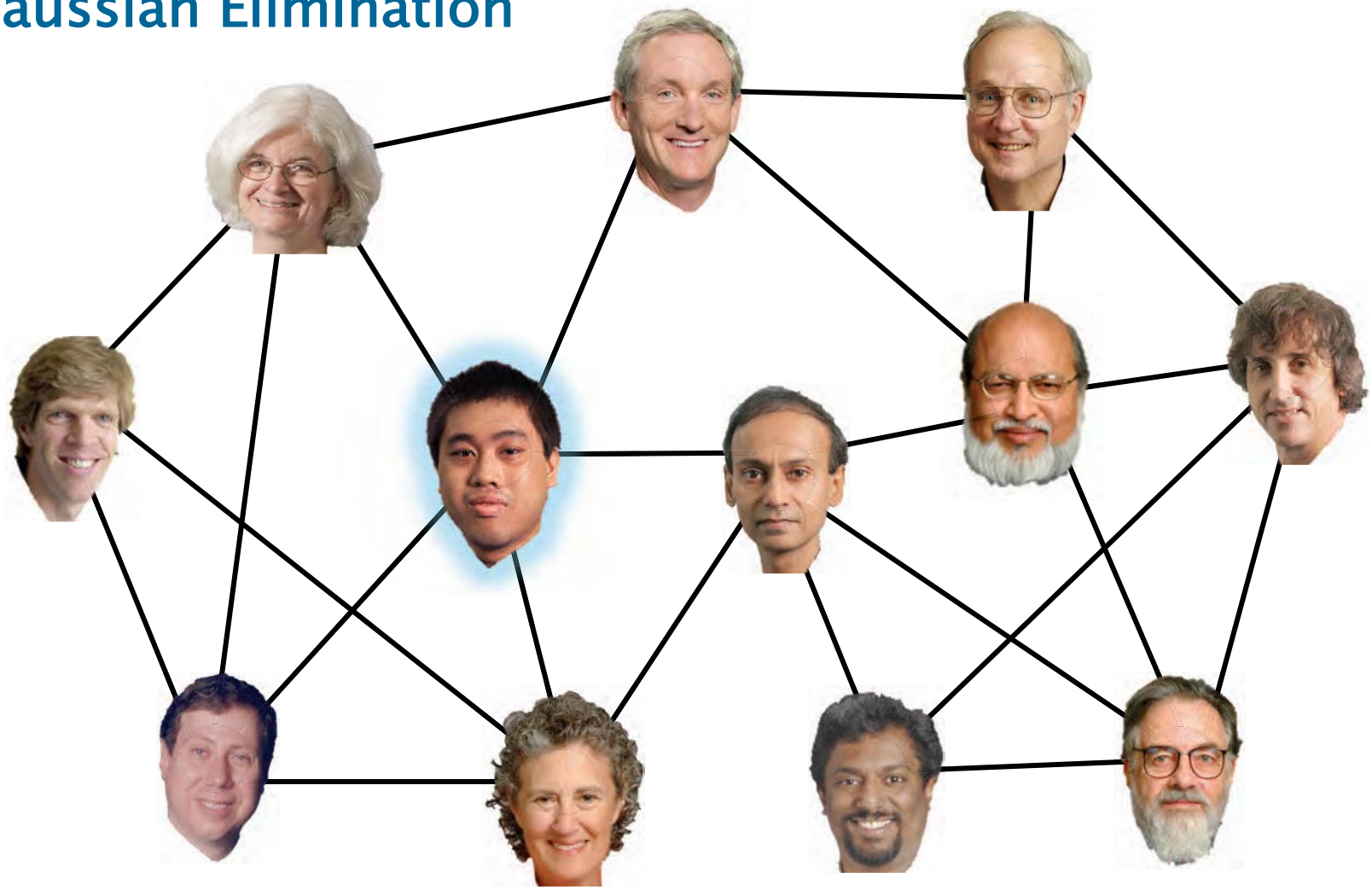
Concurrent Graph Computation

Gaussian Elimination



Concurrent Graph Computation

Gaussian Elimination



Concurrent Graph Computation

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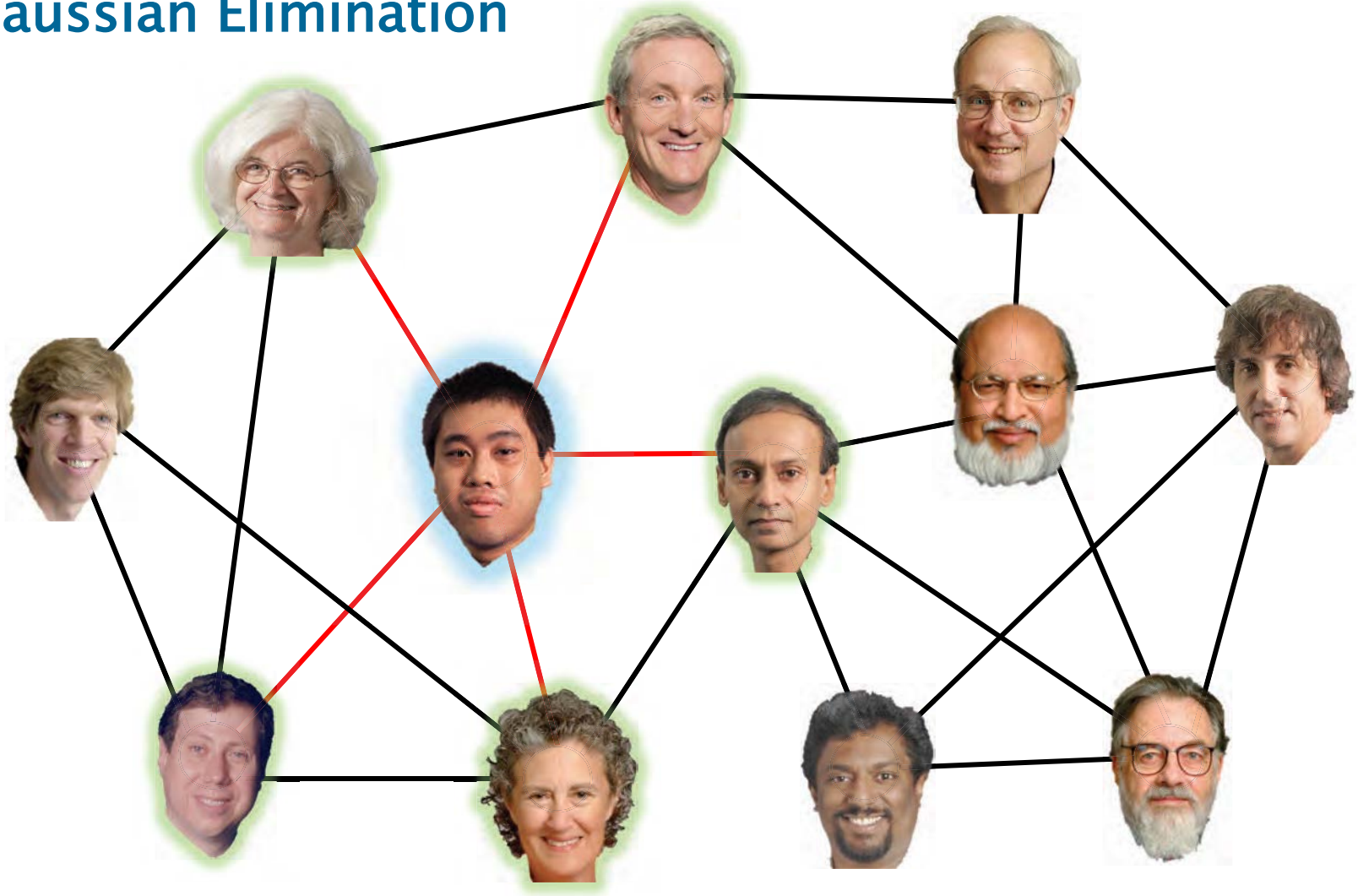
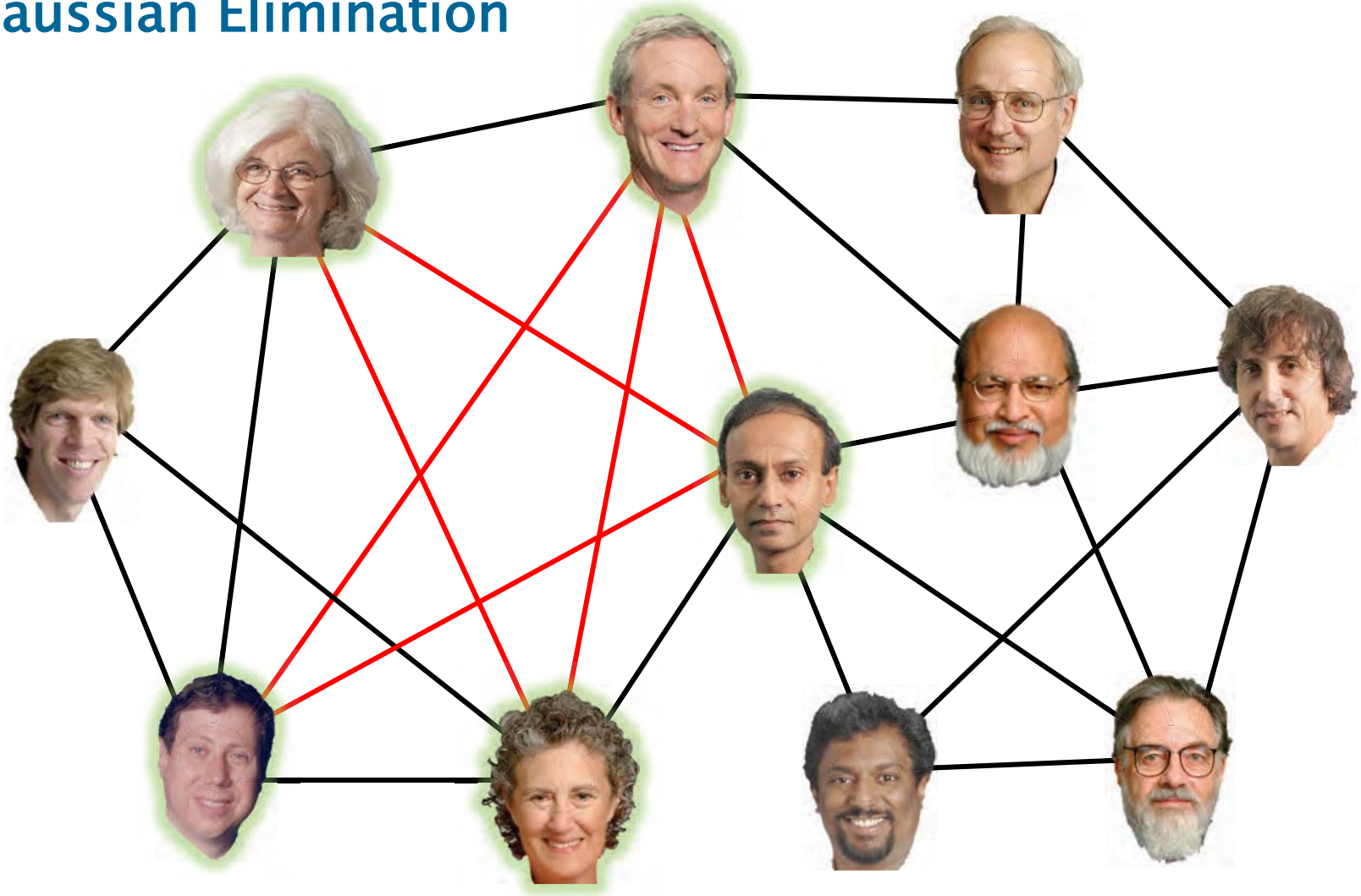


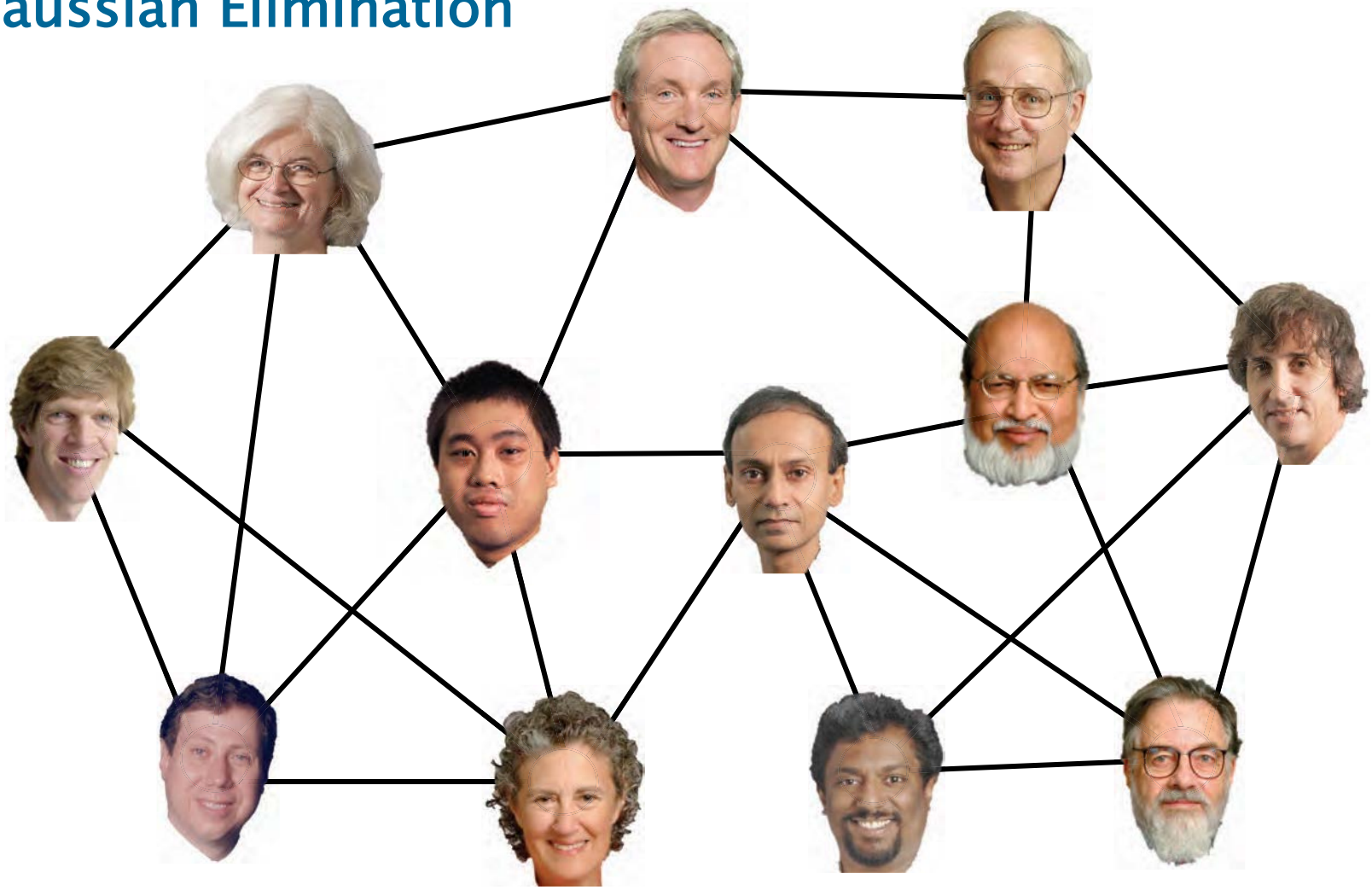
Concurrent Graph Computation

Gaussian Elimination



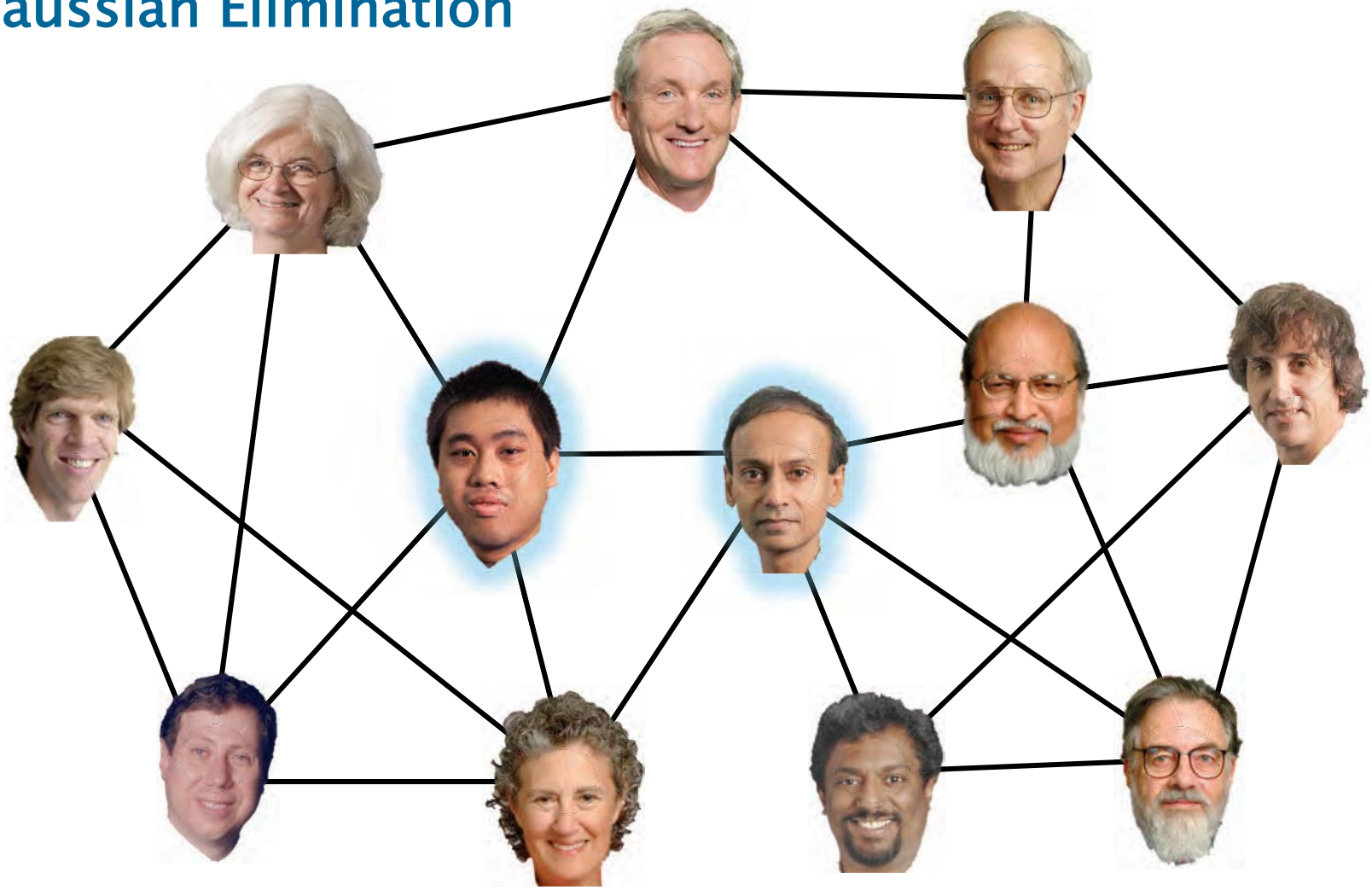
How to Deal with Concurrency?

Gaussian Elimination



How to Deal with Concurrency?

Gaussian Elimination



Transactional Memory*

```
Gaussian_Eliminate(G, v) {
  atomic {
    S = neighbors[v];
    for u ∈ S {
      E(G) = E(G) - {(u, v)};
      E(G) = E(G) - {(v, u)};
    }
    V(G) = V(G) - {v};
    for u ∈ S
      for u′ ∈ S - {u}
        E(G) = E(G) ∪ {(u, u′)};
  }
}
```

Atomicity

- On transaction commit, all memory updates in the critical region appear to take effect at once.
- On transaction abort, none of the memory updates appear to take effect, and the transaction must be restarted.
- A restarted transaction may take a different code path.

Definitions

Conflict

When two or more transactions attempt to access the same location of transactional memory concurrently.

Contention resolution

Deciding which of two conflicting transactions to wait or to abort and restart, and under what conditions.

Forward progress

Avoiding deadlock, livelock, and starvation.

Throughput

Run as many transactions concurrently as possible.

Algorithm L [L16]

Assume that the transactional-memory system provides mechanisms for

- logging reads and writes,
- aborting and rolling back transactions,
- restarting.

Algorithm L employs a lock-based approach that combines two ideas:

- finite ownership array [HF03],
- release-sort-reacquire [L95, RFF06].

Finite Ownership Array

- An array `lock[0..n-1]` of antistarvation (queuing) mutual-exclusion locks,* which support:
  - ACQUIRE(`l`): Grab lock `l`, blocking until it becomes available.
  - TRY_ACQUIRE(`l`): Try to grab lock `l`, and return `true` or `false` to indicate success or failure, respectively.
  - RELEASE(`l`): Release lock `l`.
- An owner function $h: U \to \{0, 1, \ldots, n-1\}$ mapping the space `U` of memory locations to indexes in `lock`.
- To lock location $x \in U$, acquire `lock[h(x)]`.

---

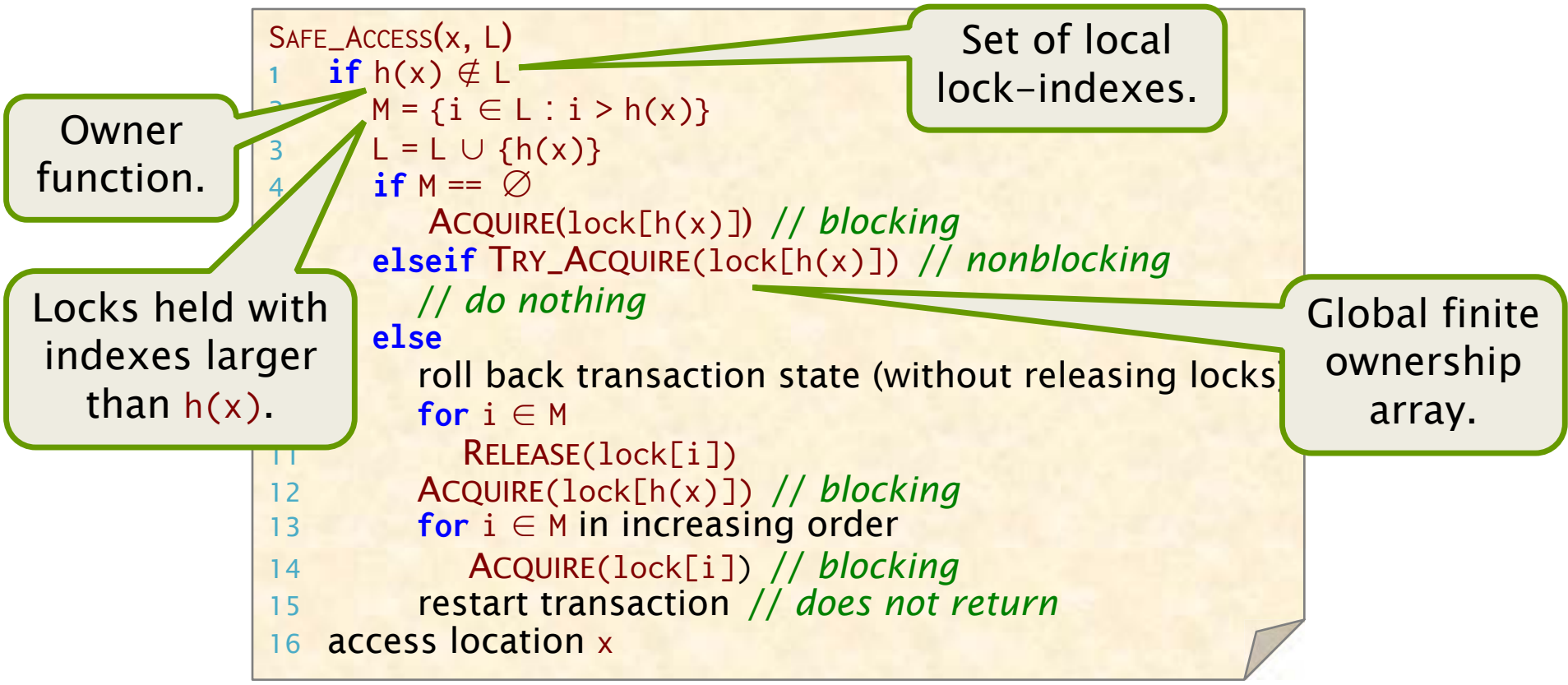
*For greater generality, one can use reader/writer locks.

Release-Sort-Reacquire

Before accessing a memory location `x`, try to acquire `lock[h(x)]` greedily. On conflict (i.e., the lock is already held):

1. Roll back the transaction (without releasing locks).
2. Release all locks with indexes larger than `h[x]`.
3. Acquire `lock[h(x)]`, blocking if already held.
4. Reacquire the released locks in sorted order, blocking if already held.
5. Restart the transaction.

Algorithm L



Safely access a memory location x within a transaction having local lock-index set L.

- At transaction start, the transaction's lock-index set L is initialized to the empty set: L = ∅.
- When the transaction completes, all locks with indexes in L are released.

Forward Progress (1)

Before accessing a memory location `x`, try to acquire `lock[h(x)]` greedily. On conflict (i.e., the lock is already held):

1. Roll back the transaction (without releasing locks).
2. Release all locks with indexes larger than `h[x]`.
3. Acquire `lock[h(x)]`, blocking if already held.
4. Reacquire the released locks in sorted order, blocking if already held.
5. Restart the transaction.

No deadlocks

A transaction only blocks when waiting for a lock larger than any of the locks it already holds ⇒ no deadly embrace, i.e., no cycle of blocking.

Forward Progress (2)

Before accessing a memory location `x`, try to acquire `lock[h(x)]` greedily. On conflict (i.e., the lock is already held):

1. Roll back the transaction (without releasing locks).
2. Release all locks with indexes larger than `h[x]`.
3. Acquire `lock[h(x)]`, blocking if already held.
4. Reacquire the released locks in sorted order, blocking if already held.
5. Restart the transaction.

No livelocks or starvation

Each time a transaction restarts, it holds at least one more lock than it held the previous time. Thus, a transaction can be attempted at most `n` times, where `n` is the size of the ownership array.

Remarks

Properly choosing the length n of the ownership-array is crucial:

- The smaller n is, the more the false contention.
- The larger n is, the weaker the forward-progress guarantee.
- If the owner function h is random, by the birthday paradox, the number of "false" conflicts is at most 1 if $n = m^2/2$, where m is the total number of shared-memory locations in all concurrently running transactions.

As a practical matter, timestamp-based algorithms seem to be the preferred method for guaranteeing forward progress:

- wound-wait and wait-die [RSL78],
- TL2 [DSS06],
- provable bounds [GHP05].

But these algorithms tend to be complex.

Locking Anomaly: Convoying

Convoying

A lock *convoy* occurs when multiple threads of equal priority contend repeatedly for the same lock.

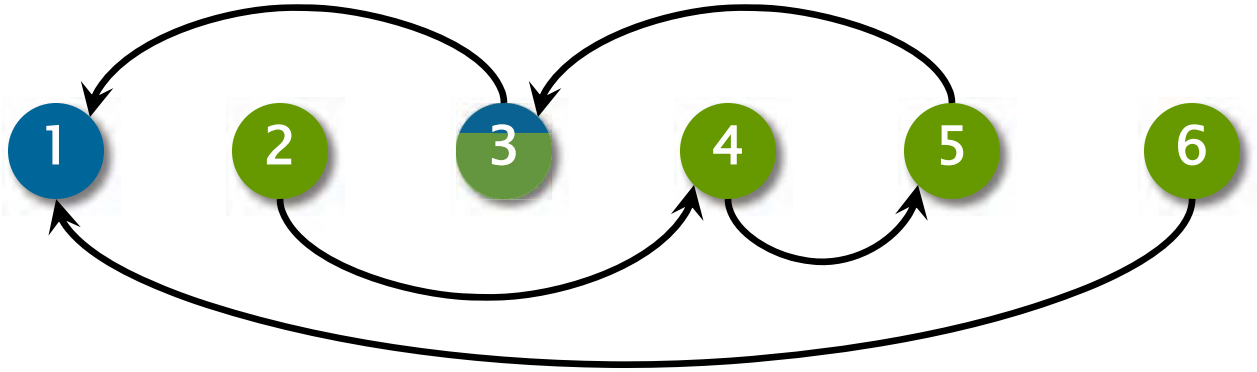
Example: Performance bug in MIT-Cilk

When random work-stealing, each thief grabs a mutex on its victim's deque:

- If the victim's deque is empty, the thief releases the mutex and tries again at random.
- If the victim's deque contains work, the thief steals the topmost frame and then releases the mutex.

PROBLEM: At start-up, most thieves quickly converge on the worker containing the initial strand, creating a **convoy**.

Performance Bug in MIT-Cilk



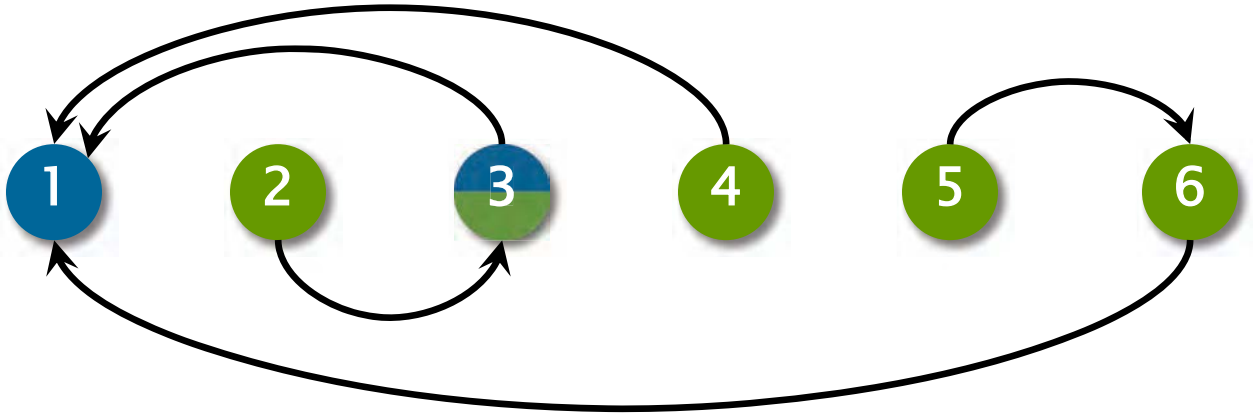
: busy worker

3 : successful steal in progress

: idle worker

: dependency from onto the lock on 's deque

Performance Bug in MIT-Cilk



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: idle worker

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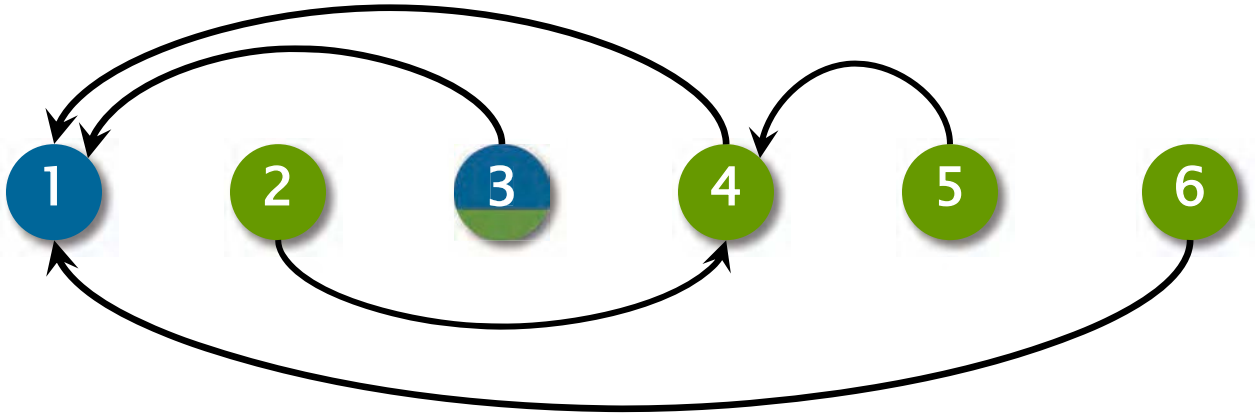
Performance Bug in MIT-Cilk



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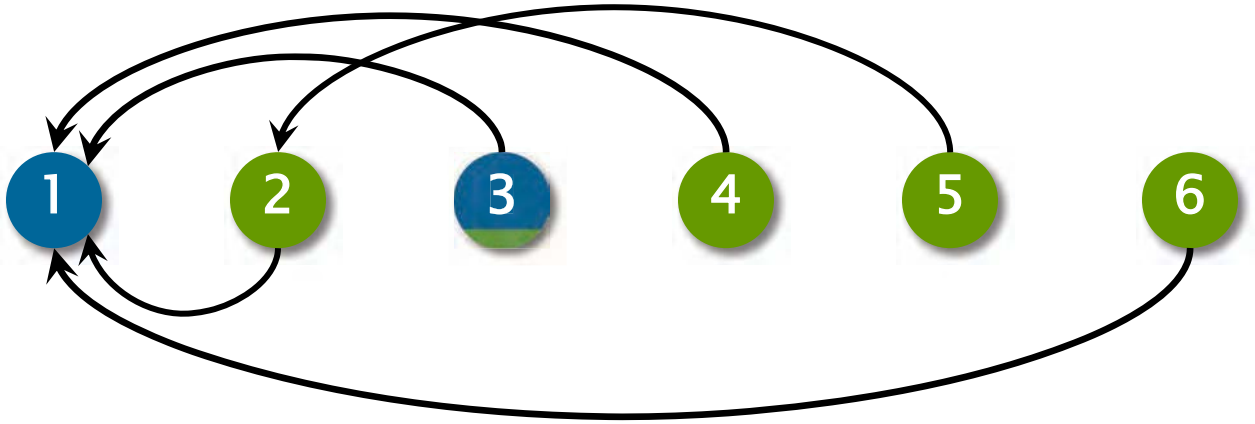
Performance Bug in MIT-Cilk



: busy worker

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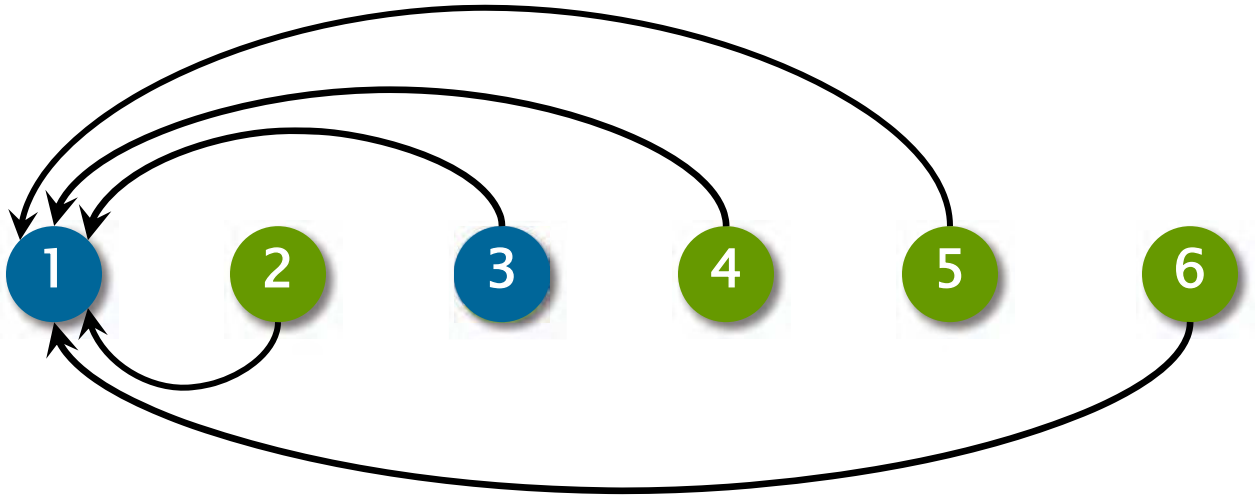

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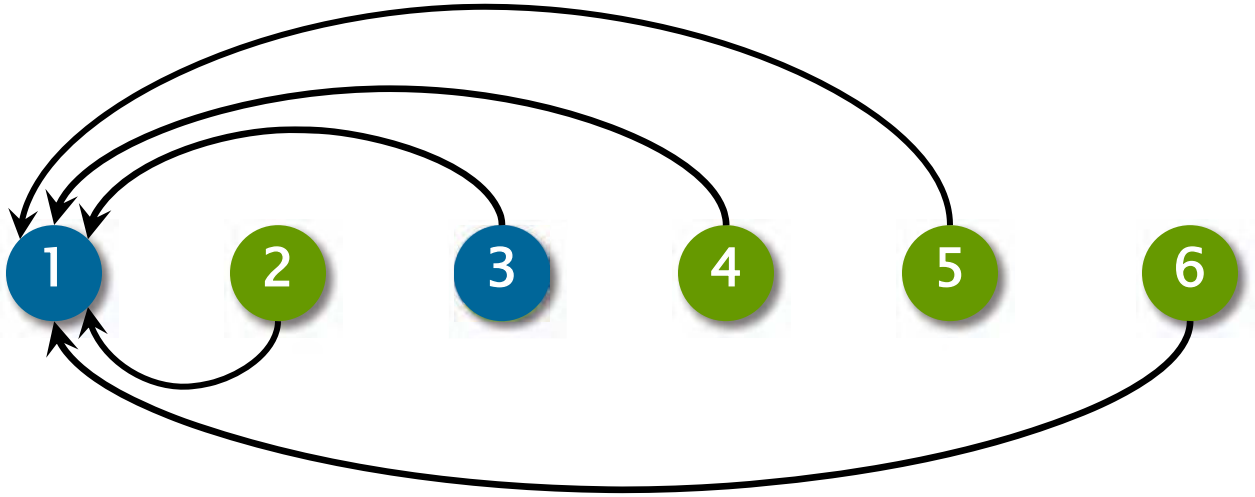
Performance Bug in MIT-Cilk



The work now gets distributed slowly as each thief serially obtains Processor 1's mutex.

Solving the Convoying Problem

Use the nonblocking function `try_lock()`, rather than `lock()`:

- `try_lock()` attempts to acquire the mutex and returns a flag indicating whether it was successful, but it does not block on an unsuccessful attempt.

In Cilk Plus, when a thief fails to acquire a mutex, it simply tries to steal again at random, rather than blocking.

Locking Anomaly: Contention

Summing Example

```
int compute(const X& v);
int main() {
  const size_t n = 1000000;
  extern X myArray[n];
  // ...

  int result = 0;
  for (size_t i = 0; i < n; ++i) {
    result += compute(myArray[i]);
  }
  printf("The result is: %d\n”, result);

  return 0;
}
```

Summing Example in Cilk

```
int compute(const X& v);
int main() {
  const size_t n = 1000000;
  extern X myArray[n];
  // ...

  int result = 0;
  cilk_for (size_t i = 0; i < n; ++i) {
    result += compute(myArray[i]);
  }
  printf("The result is: %d\n", result);

  return 0;
}
```

Assume $\Theta(1)$ work.

Race!

Work/span theory

$T_1(n) = \Theta(n)$

$T_\infty(n) = \Theta(\lg n)$

$T_P(n) = O(n/P + \lg n)$

Mutex Solution

```
#include <pthread.h>
int compute(const X& v);
int main() {
  const size_t n = 1000000;
  extern X myArray[n];
  // ...
  int result = 0;
  pthread_spinlock_t slock;
  pthread_spin_init(&slock, 0);
  cilk_for (size_t i = 0; i < n; ++i) {
    pthread_spin_lock(&slock);
      result += compute(myArray[i]);
    pthread_spin_unlock(&slock);
  }
  printf("The result is: %d\n", result);

  return 0;
}
```

Lock contention
⇒ no parallelism!

Contention

$T_1(n) = \Theta(n)$
$T_\infty(n) = \Theta(\lg n)$
$T_P(n) = \Omega(n)$

Scheduling with Mutexes

Greedy scheduler:

$$T_P \leq T_1/P + T_\infty + B \ ,$$

where B is the **bondage** — the total time of all critical sections.

This upper bound is weak, especially if many small mutexes each protect different critical regions. Little is known theoretically about lock contention.

Golden Rule of Parallel Programming

Silver Rule of Parallel Programming

Never write nondeterministic parallel programs

— but if you must —

always devise a test strategy to manage the nondeterminism!

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