Models of concurrency & synchronization algorithms

Lesson 3 of TDA384/DIT391

Principles of Concurrent Programming

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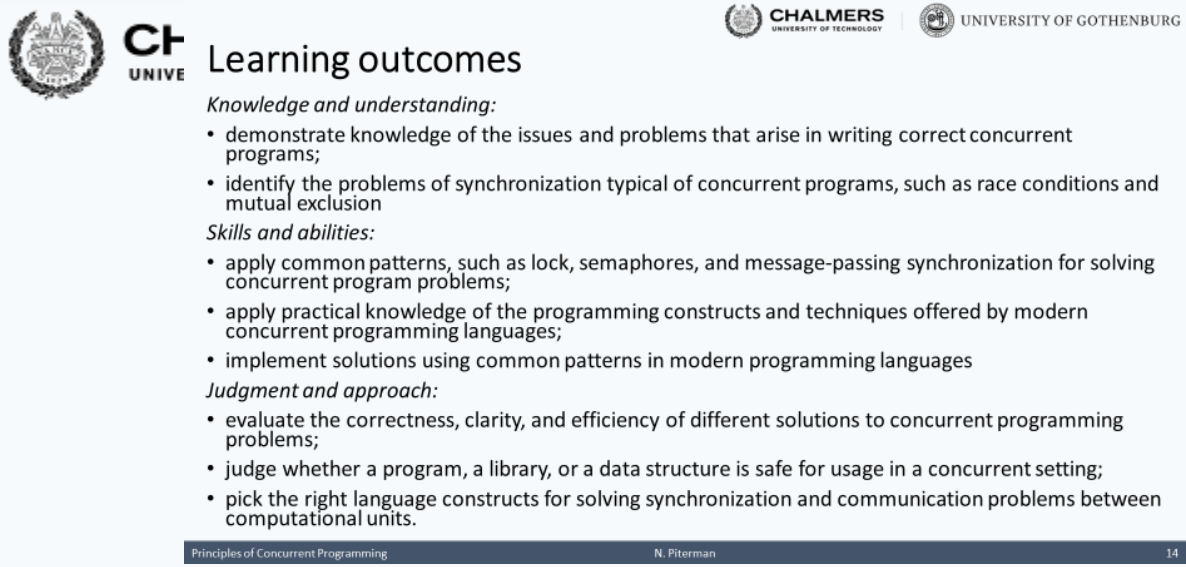
Lesson's menu

- Analyzing concurrency
- Mutual exclusion with only atomic reads and writes
  - Three failed attempts
  - Peterson's algorithm
  - Mutual exclusion with bounded waiting
- Implementing mutual exclusion algorithms in Java
- Implementing semaphores

Lesson's menu

- Analyzing concurrency
  - Evaluate correctness of solutions
  - Important for understanding of race conditions
- Mutual exclusion with only atomic reads and writes
  - Understand the issues and problems
    - Interleaving and races
    - Why stronger synchronization
  - What's not working and what's working
- Implementing mutual exclusion algorithms in Java
  - Better understanding of Java memory model
  - More language constructs
  - Undrestanding exact behavior
- Implementing semaphores
  - Understand exact behavior
  - Demonstrate issues and problems



Analyzing concurrency

State/transition diagrams

We capture essential elements of concurrent programs using state/transition diagrams

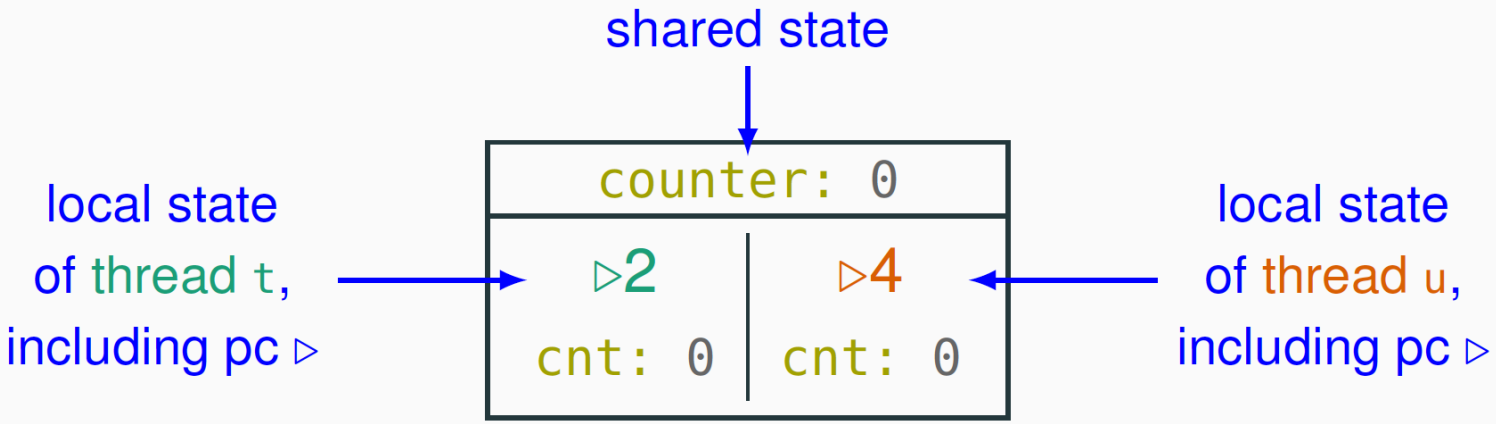
- Also called: *(finite) state automata*, *(finite) state machines*, or *transition systems*

- States in a diagram capture possible program states
- Transitions connect states according to execution order

Structural properties of a diagram capture semantic properties of the corresponding program

States

A state captures the shared and local states of a concurrent program:



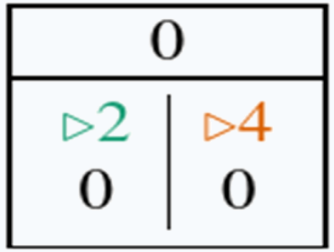

```
int counter = 0;
```

thread t		thread u	
`int cnt;`		`int cnt;`	
1 `cnt = counter;`		`cnt = counter;`	3
2 `counter = cnt + 1;`		`counter = cnt + 1;`	4

States

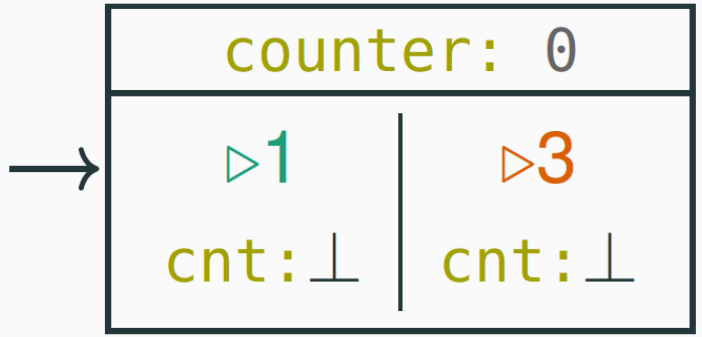
A state captures the shared and local states of a concurrent program:

When unambiguous, we simplify a state with only the essential information:



Initial states

The initial state of a computation is marked with an incoming arrow:

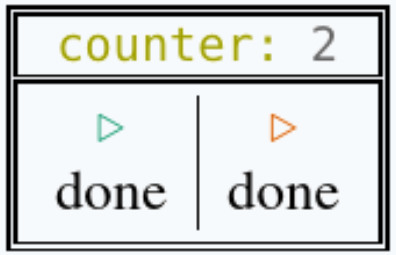



```
int counter = 0;
```

thread t	thread u
`int cnt;`	`int cnt;`
1 `cnt = counter;`	`cnt = counter;` 3
2 `counter = cnt + 1;`	`counter = cnt + 1;` 4

Final states

The final states of a computation – where the program terminates – are marked with double-line edges:

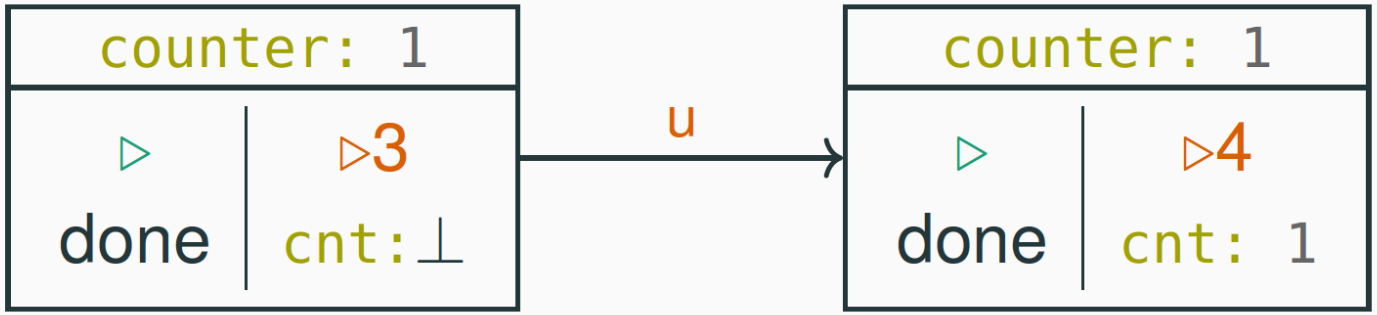



```
int counter = 0;
```

thread t	thread u
`int cnt;`	`int cnt;`
1 `cnt = counter;`	`cnt = counter;` 3
2 `counter = cnt + 1;`	`counter = cnt + 1;` 4

Transitions

A transition corresponds to the execution of one atomic instruction, and it is an arrow connecting two states (or a state to itself):

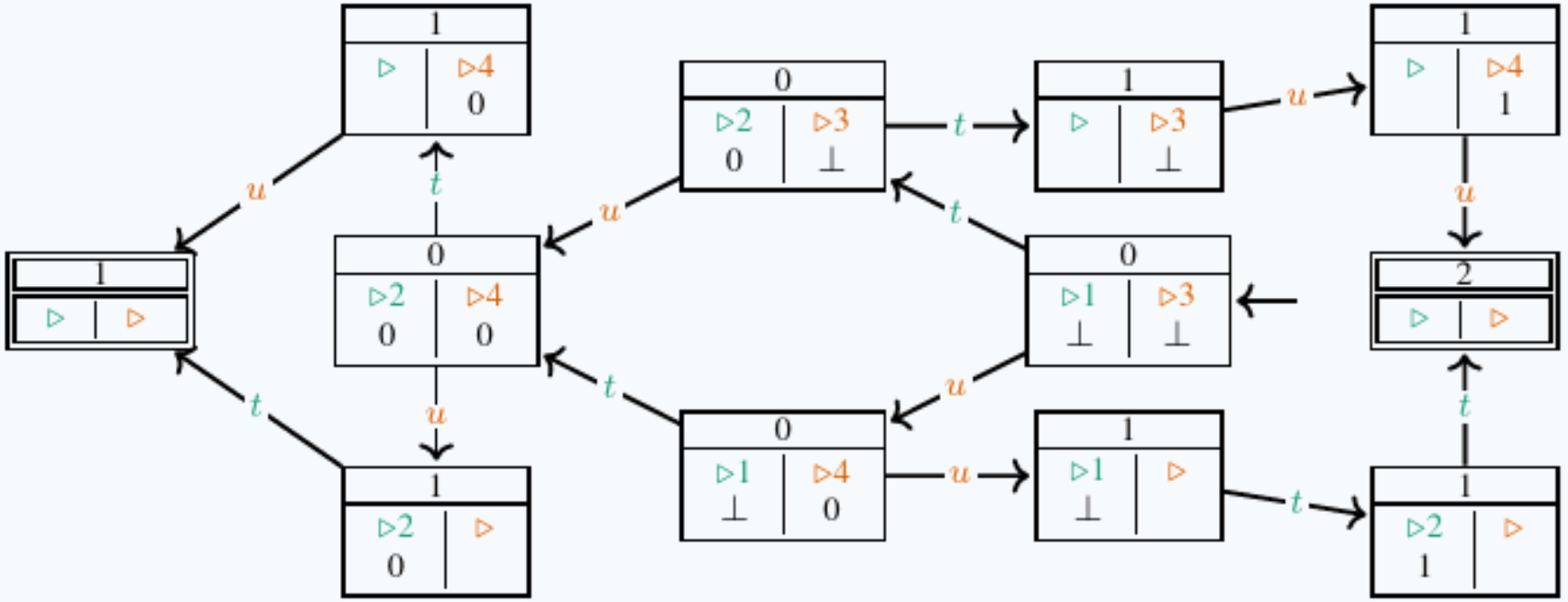



```
int counter = 0;
```

thread t		thread u	
`int cnt;`		`int cnt;`	
1 `cnt = counter;`		`cnt = counter;`	3
2 `counter = cnt + 1;`		`counter = cnt + 1;`	4

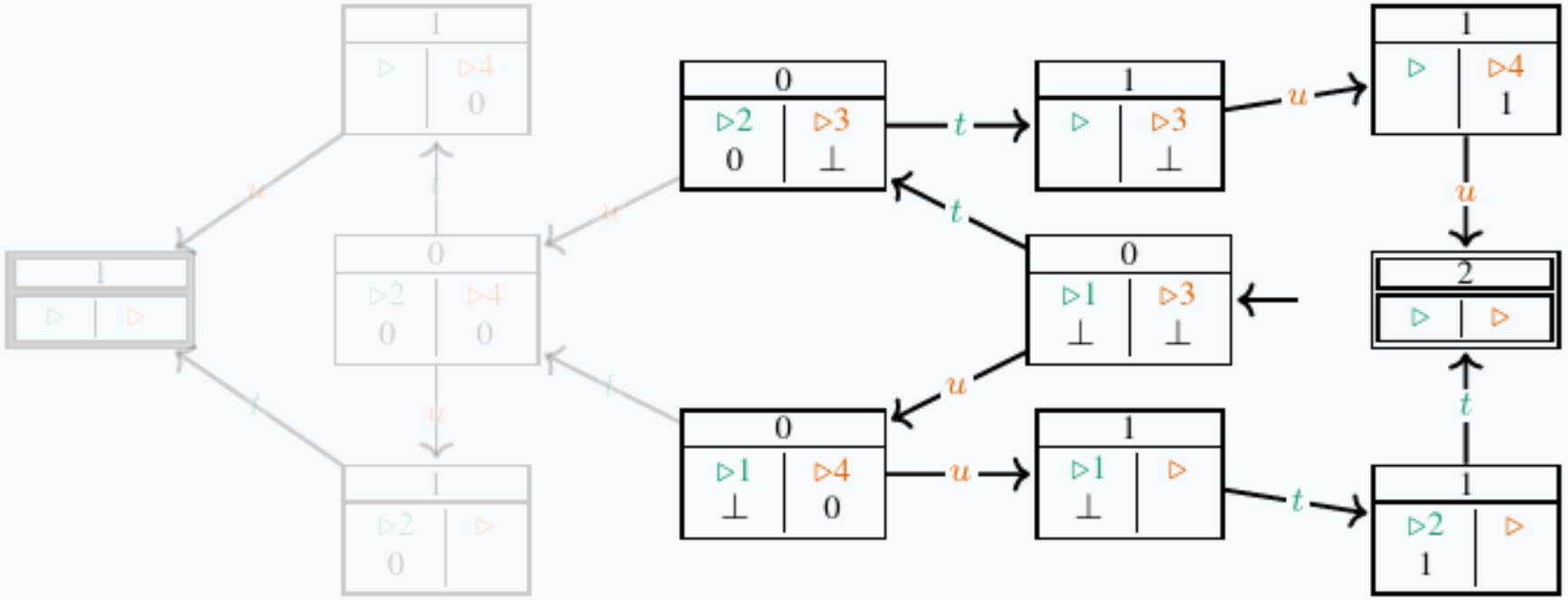
A complete state/transition diagram

The complete **state/transition diagram** for the concurrent counter example explicitly shows all possible interleavings:



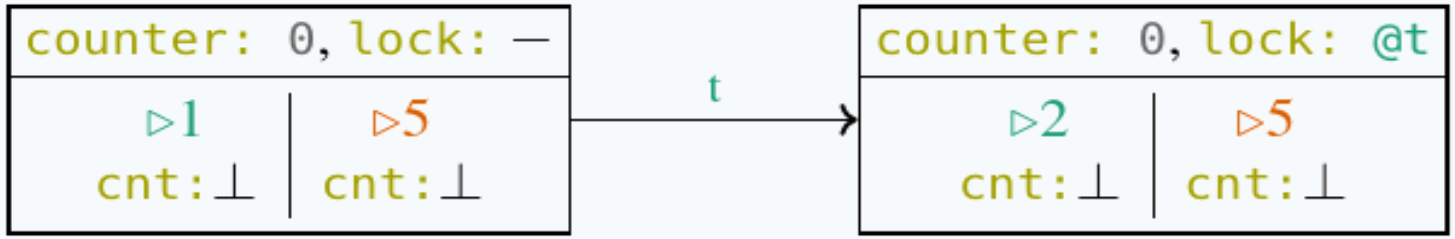
State/transition diagram with locks?

The state/transition diagram of the concurrent counter example we would like to achieve using **locks**:



Locking

Locking and unlocking are considered atomic operations




```
int counter = 0;     Lock lock = new Lock();
```

thread t

```
int cnt;

1  lock.lock();
2    cnt = counter;
3    counter = cnt + 1;
4  lock.unlock();
```

thread u

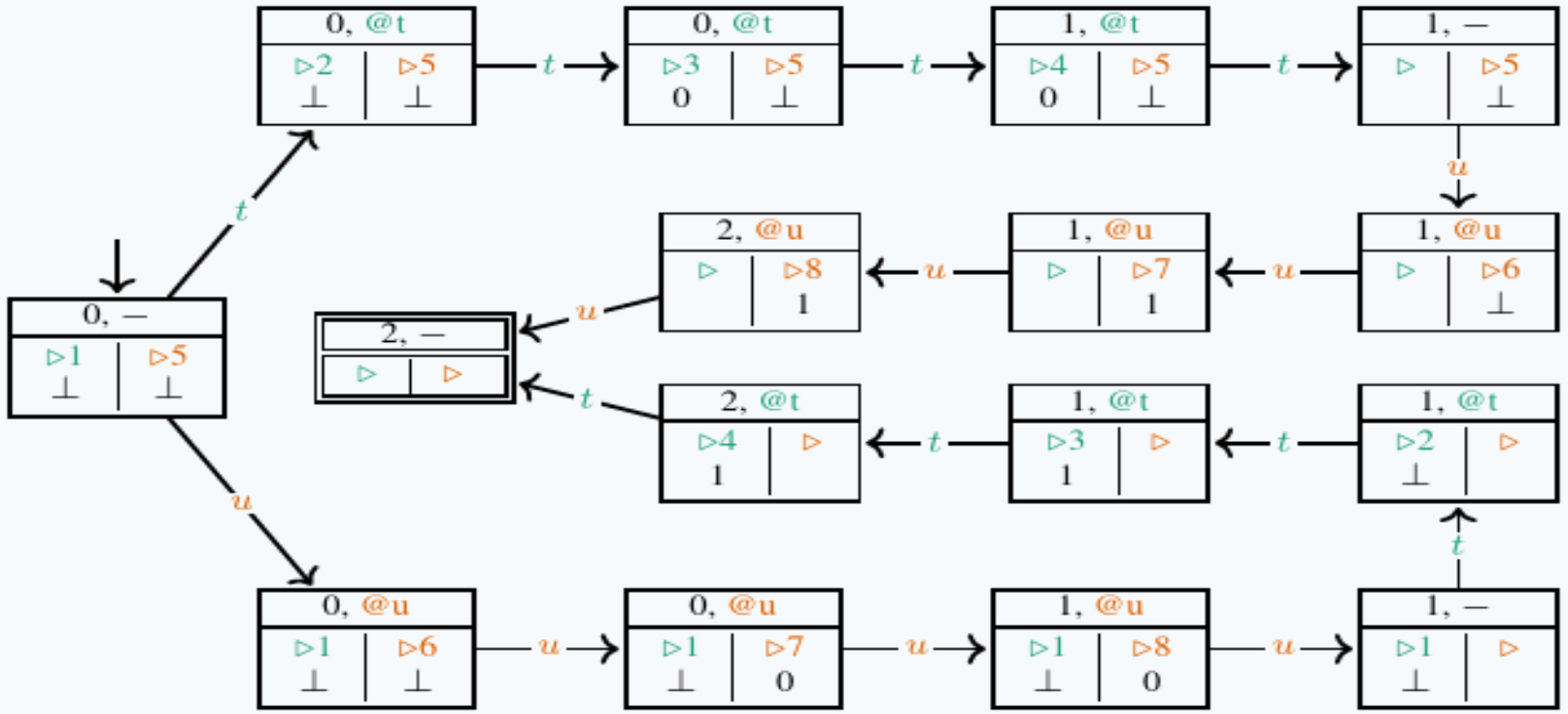
```
int cnt;

lock.lock();                5
  cnt = counter;            6
  counter = cnt + 1;        7
lock.unlock();              8
```

This transition is only allowed if the lock is not held by another thread

Counter with locks: state/transition diagram

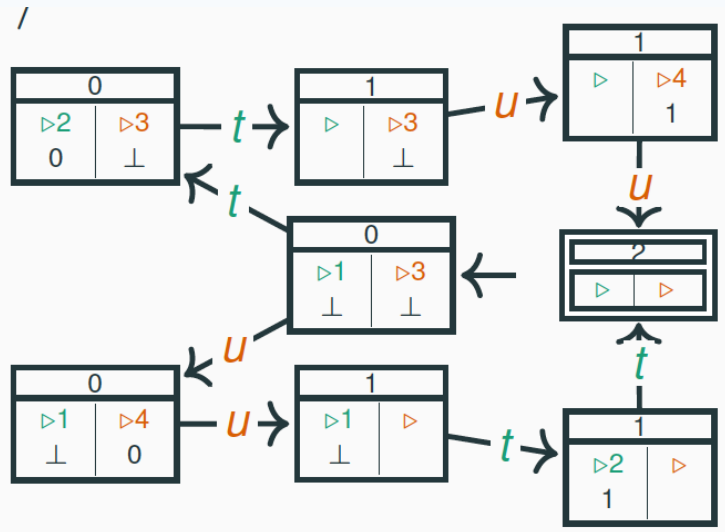
The state/transition diagram of the concurrent counter example **using locks** should contain no (states representing) race conditions:



Transition tables

Transition tables are ***equivalent representations*** of the information of state/transition diagrams

CURRENT	NEXT WITH t	NEXT WITH u
$\langle 0, \triangleright 1, \bot, \triangleright 3, \bot \rangle$	$\langle 0, \triangleright 2, 0, \triangleright 3, \bot \rangle$	$\langle 0, \triangleright 1, \bot, \triangleright 4, 0 \rangle$
$\langle 0, \triangleright 2, 0, \triangleright 3, \bot \rangle$	$\langle 1, \triangleright\ ,\ , \triangleright 3, \bot \rangle$	—
$\langle 0, \triangleright 1, \bot, \triangleright 4, 0 \rangle$	—	$\langle 1, \triangleright 1, \bot, \triangleright\ ,\ \rangle$
$\langle 1, \triangleright\ ,\ , \triangleright 3, \bot \rangle$	—	$\langle 1, \triangleright\ ,\ , \triangleright 4, 1 \rangle$
$\langle 1, \triangleright 1, \bot, \triangleright\ ,\ \rangle$	$\langle 1, \triangleright 2, 1, \triangleright\ ,\ \rangle$	—
$\langle 1, \triangleright\ ,\ , \triangleright 4, 1 \rangle$	—	$\langle 2, \triangleright\ ,\ , \triangleright\ ,\ \rangle$
$\langle 1, \triangleright 2, 1, \triangleright\ ,\ \rangle$	$\langle 2, \triangleright\ ,\ , \triangleright\ ,\ \rangle$	—
$\langle 2, \triangleright\ ,\ , \triangleright\ ,\ \rangle$	—	—



Reasoning about program properties

The structural properties of a diagram capture semantic properties of the program:

Mutual exclusion: there are no states where two threads are in their critical section

Deadlock freedom: for every (non-final) state, there is an outgoing transition

Starvation freedom: there is no (looping) path such that a thread never enters its critical section while trying to do so

No race conditions: all the final states have the same (correct) result

- We will build and analyze state/transition diagrams only for simple examples, since it quickly becomes tedious
- Model checking is a technique that automates the construction and analysis of state/transition diagrams with billions of states
  - We'll give a short introduction to model checking in one of the last classes

Mutual exclusion with only atomic reads and writes

Locks: recap

A lock is a data structure (an object in Java) with interface:

```
interface Lock {
  void lock();      // acquire lock
  void unlock();    // release lock
}
```

- Several threads share the same object **`lock`** of type **`Lock`**
- Threads calling **`lock.lock()`**: exactly one thread *t* acquires the lock:
  - *t*'s call **`lock.lock()`** returns: *t* is holding the lock
  - other threads block on the call **`lock.lock()`**, waiting for the lock to become available
- A thread *t* that is holding the lock calls **`lock.lock()`** to release the lock:
  - *t*'s call **`lock.unlock()`** returns: the lock becomes available
  - another thread waiting for the lock may succeed in acquiring it

Mutual exclusion **without** locks

Can we implement locks using only atomic instructions – reading and writing shared variables?

- It is possible
- But it is also tricky!

- We present some classical algorithms for mutual exclusion using only **atomic reads** and **writes**
  - The presentation builds up to the correct algorithms in a series of attempts, which highlight the principles that underlie how the algorithms work

The mutual exclusion problem - recap

Given N threads, each executing:

```
// continuously
while (true) {
  entry protocol
  critical section {
    // access shared data
  }
  exit protocol
} /* ignore behavior
outside critical section */
```

Now protocols can use *only* reads and writes of shared variables

Design the entry and exit protocols to ensure:

- mutual exclusion
- freedom from deadlock
- freedom from starvation

Initially we limit ourselves to $N = 2$ threads, t_0 and t_1

Busy waiting

In the pseudo-code, we will use the shorthand

```
await(c) ≜   while (!c)   {}
```

to denote busy waiting (also called spinning):

- keep reading shared variable `c` as long as it is `false`
- proceed when it becomes `true`

- Busy waiting is generally inefficient (unless typical waiting times are shorter than context switching times), so you should avoid using it
  - We use it only because it is a good device to illustrate the nuts and bolts of mutual exclusion protocols
- Note that `await` is **not** a valid Java keyword
  - We highlight it in a different color – but we will use it as a shorthand for better readability

Mutual exclusion with only atomic reads and writes

Three *failed* attempts

Double-threaded mutual exclusion: **First** naive attempt

Use Boolean flags `enter[0]` and `enter[1]`:

- each thread waits until the other thread is not trying to enter the critical section
- before thread t_k is about to enter the critical section, it sets enter[k] to true

```
boolean[] enter = {false, false};
```

thread t_0

```
1  while (true) {
2    // entry protocol
3    await (!enter[1]);
4    enter[0] = true;
5    critical section { ... }
6    // exit protocol
7    enter[0] = false;
8  }
```

thread t_1

```
9  while (true) {
10   // entry protocol
11   await (!enter[0]);
12   enter[1] = true;
13   critical section { ... }
14   // exit protocol
15   enter[1] = false;
16 }
```

The **first** naive attempt is incorrect!

The **first attempt** does **not guarantee** mutual exclusion: t_0 and t_1 can be in the critical section at the same time

```
boolean[] enter = {false, false};
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	9
2	`  // entry protocol`	`  // entry protocol`	10
3	`  await (!enter[1]);`	`  await (!enter[0]);`	11
4	`  enter[0] = true;`	`  enter[1] = true;`	12
5	`  critical section { ... }`	`  critical section { ... }`	13
6	`  // exit protocol`	`  // exit protocol`	14
7	`  enter[0] = false;`	`  enter[1] = false;`	15
8	`}`	`}`	16

Both threads here! How?

#	t_0	t_1	SHARED
1	pc_0: `await (!enter[1])`	pc_1: `await (!enter[0])`	`enter: false, false`
2	pc_0: `enter[0] = true`	pc_1: `await (!enter[0])`	`enter: false, false`
3	pc_0: `enter[0] = true`	pc_1: `enter[1] = true`	`enter: false, false`
4	pc_0: `critical section`	pc_1: `enter[1] = true`	`enter: true, false`
5	pc_0: `critical section`	pc_1: `critical section`	`enter: true, true`

The problem seems to be that **`await`** is executed before setting `enter`, so one thread may proceed ignoring that the other thread is also proceeding

Double-threaded mutual exclusion: **Second** naive attempt

When thread t_k wants to enter the **critical section**:

- it first sets `enter[k]` to true
- then it waits until the other thread is not trying to enter the critical section

```
boolean[] enter = {false, false};
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	9
2	`  // entry protocol`	`  // entry protocol`	10
3	`  enter[0] = true;`	`  enter[1] = true;`	11
4	`  await (!enter[1]);`	`  await (!enter[0]);`	12
5	`  critical section { ... }`	`  critical section { ... }`	13
6	`  // exit protocol`	`  // exit protocol`	14
7	`  enter[0] = false;`	`  enter[1] = false;`	15
8	`}`	`}`	16

The **second** naive attempt may deadlock!

The **second attempt**:

- **guarantees** mutual exclusion: t_0 is in the critical section iff `enter[1]` is false, iff t_1 has not set `enter[1]` to true, iff t_1 has not entered the critical section (t_1 has not executed line yet)
- does **not guarantee** freedom from deadlocks

Both threads might end up here, blocked. Why?

```
boolean[] enter = {false, false};
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	9
2	`  // entry protocol`	`  // entry protocol`	10
3	`  enter[0] = true;`	`  enter[1] = true;`	11
4	`  await (!enter[1]);`	`  await (!enter[0]);`	12
5	`  critical section { ... }`	`  critical section { ... }`	13
6	`  // exit protocol`	`  // exit protocol`	14
7	`  enter[0] = false;`	`  enter[1] = false;`	15
8	`}`	`}`	16

#	t_0	t_1	SHARED
1	pc_0: `enter[0] = true`	pc_1: `enter[0] = true`	enter: false, false
1	pc_0: `await (!enter[1])`	pc_1: `enter[0] = true`	enter: true, false
2	pc_0: `await (!enter[1])`	pc_1: `await (!enter[0])`	enter: true, true

The problem seems to be that the two variables `enter[0]` and `enter[1]` are accessed independently

- each thread may be waiting for permission to proceed from the other thread

Double-threaded mutual exclusion: **Third** naive attempt

Use one single integer variable `yield`:

- thread t_k waits for its turn while `yield` is k
- when it is done with its critical section, it yields control to the other thread by setting `yield = k`

```
int yield = 0 || 1; // initialize to either value
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	8
2	`  // entry protocol`	`  // entry protocol`	9
3	`  await (yield != 0);`	`  await (yield != 1);`	10
4	`  critical section { ... }`	`  critical section { ... }`	11
5	`  // exit protocol`	`  // exit protocol`	12
6	`  yield = 0;`	`  yield = 1;`	13
7	`}`	`}`	14

The **third** naive attempt **may starve** some thread!

```
int yield = 0 || 1; // initialize to either value
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	8
2	`  // entry protocol`	`  // entry protocol`	9
3	`  await (yield != 0);`	`  await (yield != 1);`	10
4	`  critical section { ... }`	`  critical section { ... }`	11
5	`  // exit protocol`	`  // exit protocol`	12
6	`  yield = 0;`	`  yield = 1;`	13
7	`}`	`}`	14

The **third attempt**:

- **guarantees** mutual exclusion:

  t_0 is in the critical section

  iff `yield` is `1`

  iff `yield` was initialized to `1` or t_1 has set `yield` to `1`

  iff t_1 is not in the critical section (t_0 has not executed line 6 yet).

- **guarantees** freedom from deadlocks: each thread enables the other thread, so that a circular wait is impossible
- does **not guarantee** freedom from starvation: if one stops executing in its **non-critical** section, the other thread will starve (after one last access to its critical section)

Later in the course: we will discuss how model checking can help to verify whether such correctness properties hold in a concurrent program

The **third** naive attempt **may starve** some thread!

```
int yield = 0 || 1; // initialize to either value
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	8
2	`  // entry protocol`	`  // entry protocol`	9
3	`  await (yield != 0);`	`  await (yield != 1);`	10
4	`  critical section { ... }`	`  critical section { ... }`	11
5	`  // exit protocol`	`  // exit protocol`	12
6	`  yield = 0;`	`  yield = 1;`	13
7	`}`	`}`	14

… then thread t_0 will starve

If `yield=0` and thread t_1 stops executing here (before the entry protocol)…

Peterson’s algorithm

Peterson's algorithm

Combine the ideas behind the second and third attempts:

- thread t_k first sets `enter[k]` to true
- but lets the other thread go first – by setting `yield`

```
boolean[] enter = {false, false};   int yield = 0 || 1;
```

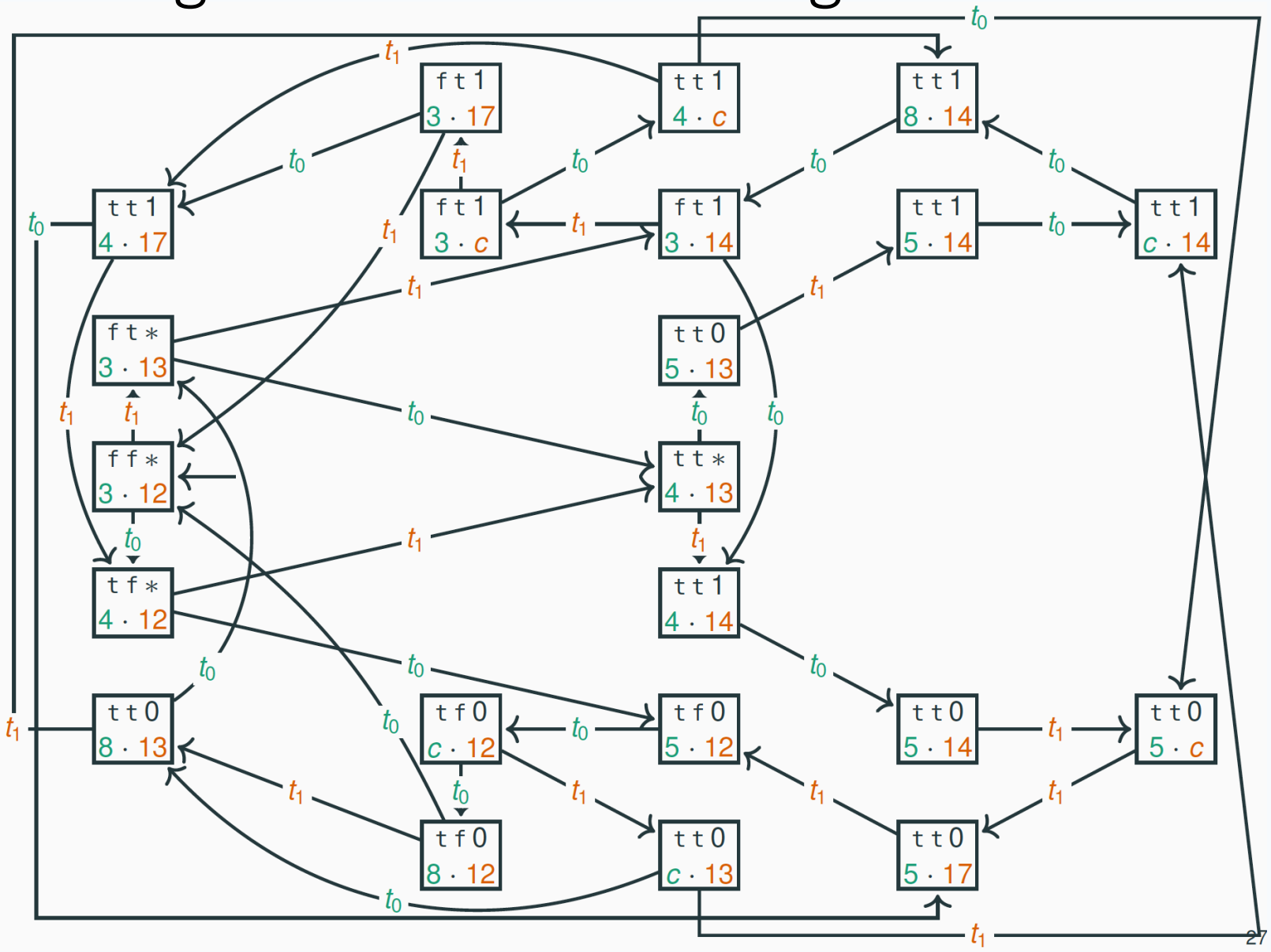
thread t_0		thread t_1	
`while (true) {`	1	`while (true) {`	10
`// entry protocol`	2	`// entry protocol`	11
`enter[0] = true;`	3	`enter[1] = true;`	12
`yield = 0;`	4	`yield = 1;`	13
`await (!enter[1] || yield != 0);`	5	`await (!enter[0] || yield != 1);`	14
`critical section { ... }`	6	`critical section { ... }`	15
`// exit protocol`	7	`// exit protocol`	16
`enter[0] = false;`	8	`enter[1] = false;`	17
`}`	9	`}`	18

Equivalent to:
wait while
(enter[1]=true
&
yield=0)

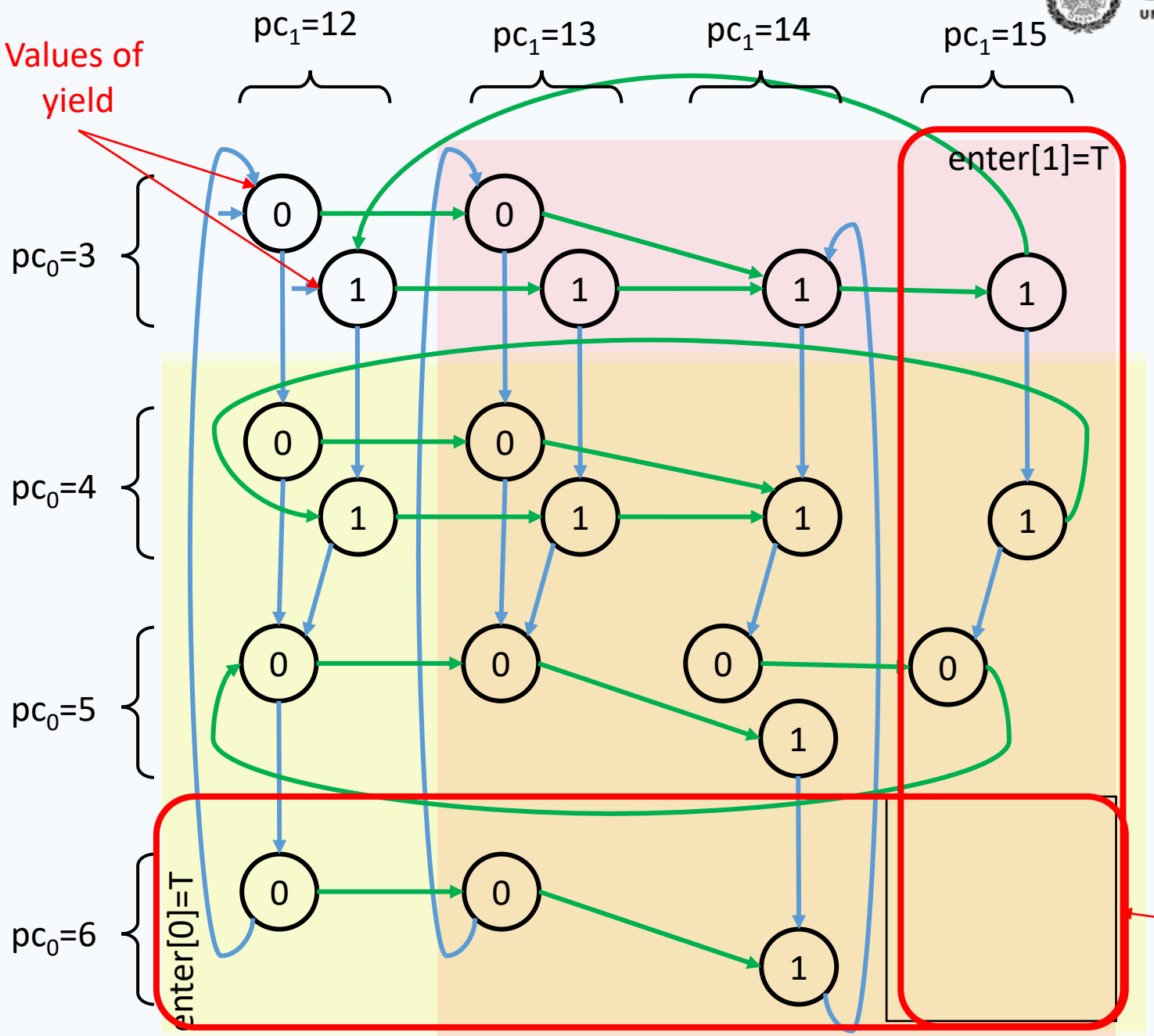
Enter only when
(enter[1]=false
OR
yield=1)

Works even if two reads are non-atomic

State/transition diagram of Peterson's algorithm



Another state/transition diagram of Peterson's algorithm




```
boolean[] enter = {false, false};   int yield = 0 || 1;
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	10
2	`  // entry protocol`	`  // entry protocol`	11
3	`  enter[0] = true;`	`  enter[1] = true;`	12
4	`  yield = 0;`	`  yield = 1;`	13
5	`  await (!enter[1] || yield != 0);`	`  await (!enter[0] || yield != 1);`	14
6	`  critical section { ... }`	`  critical section { ... }`	15
7	`  // exit protocol`	`  // exit protocol`	16
8	`  enter[0] = false;`	`  enter[1] = false;`	17
9	`}`	`}`	18

Critical Section

Omitting lines 7-9 and 16-18

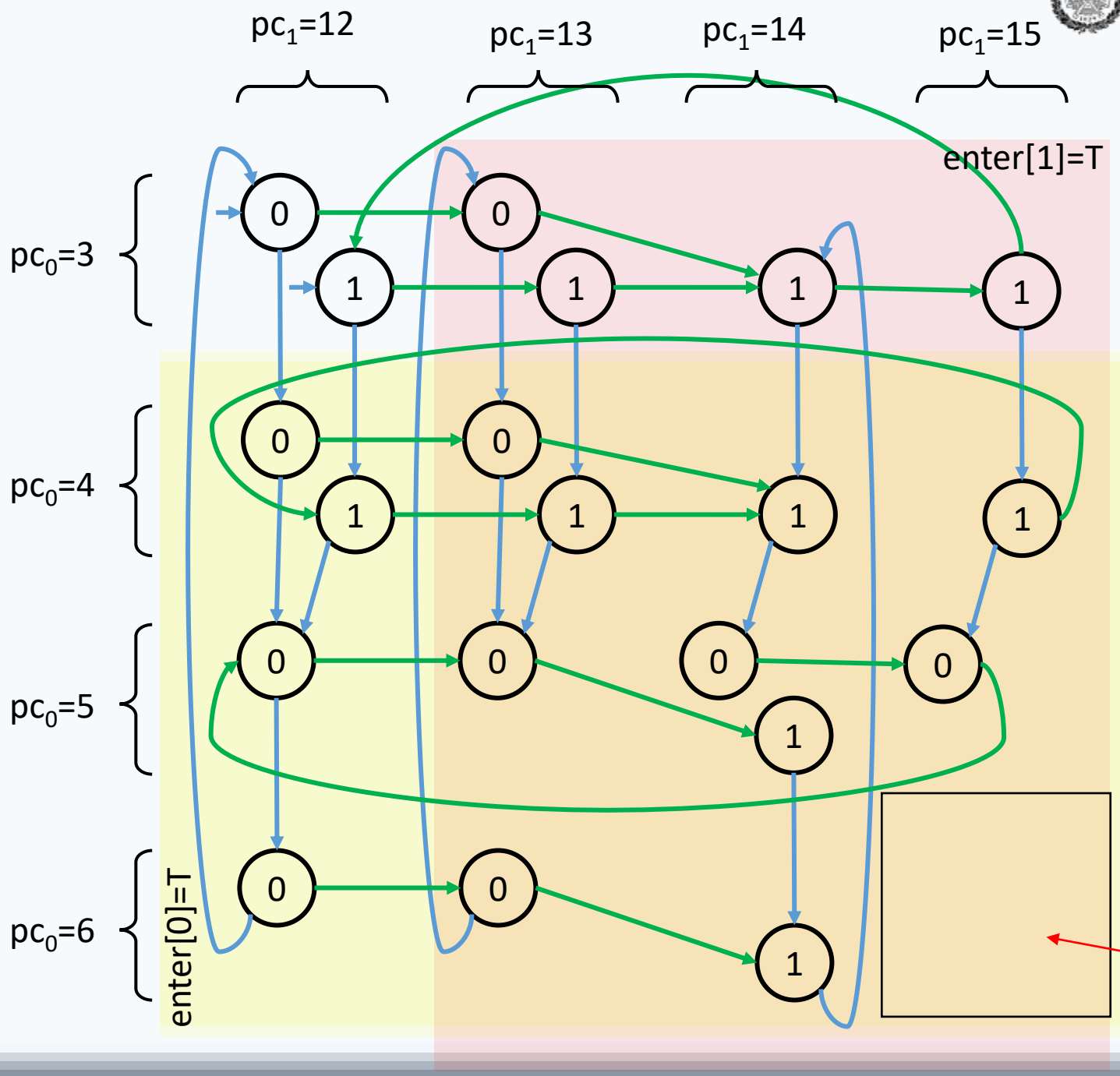
Checking the correctness of Peterson's algorithm

By inspecting the state/transition diagram, we can check that Peterson's algorithm satisfies:

mutual exclusion: there are no states where both threads are at pc0=6 and pc1=15 (in the critical section)

deadlock freedom: every state has at least one outgoing transition

starvation freedom: if thread t_0 is in its critical section, then thread t_1 can reach its critical section without requiring thread t_0's collaboration after t_0 executes the exit protocol



Peterson's algorithm satisfies **mutual exclusion** and is **deadlock free**

```
boolean[] enter = {false, false};   int yield = 0 || 1;
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	10
2	`  // entry protocol`	`  // entry protocol`	11
3	`  enter[0] = true;`	`  enter[1] = true;`	12
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5	`  await (!enter[1] || yield != 0);`	`  await (!enter[0] || yield != 1);`	14
6	`  critical section { ... }`	`  critical section { ... }`	15
7	`  // exit protocol`	`  // exit protocol`	16
8	`  enter[0] = false;`	`  enter[1] = false;`	17
9	`}`	`}`	18

Both in Critical Section

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By inspecting the state/transition diagram, we can check that Peterson's algorithm satisfies:

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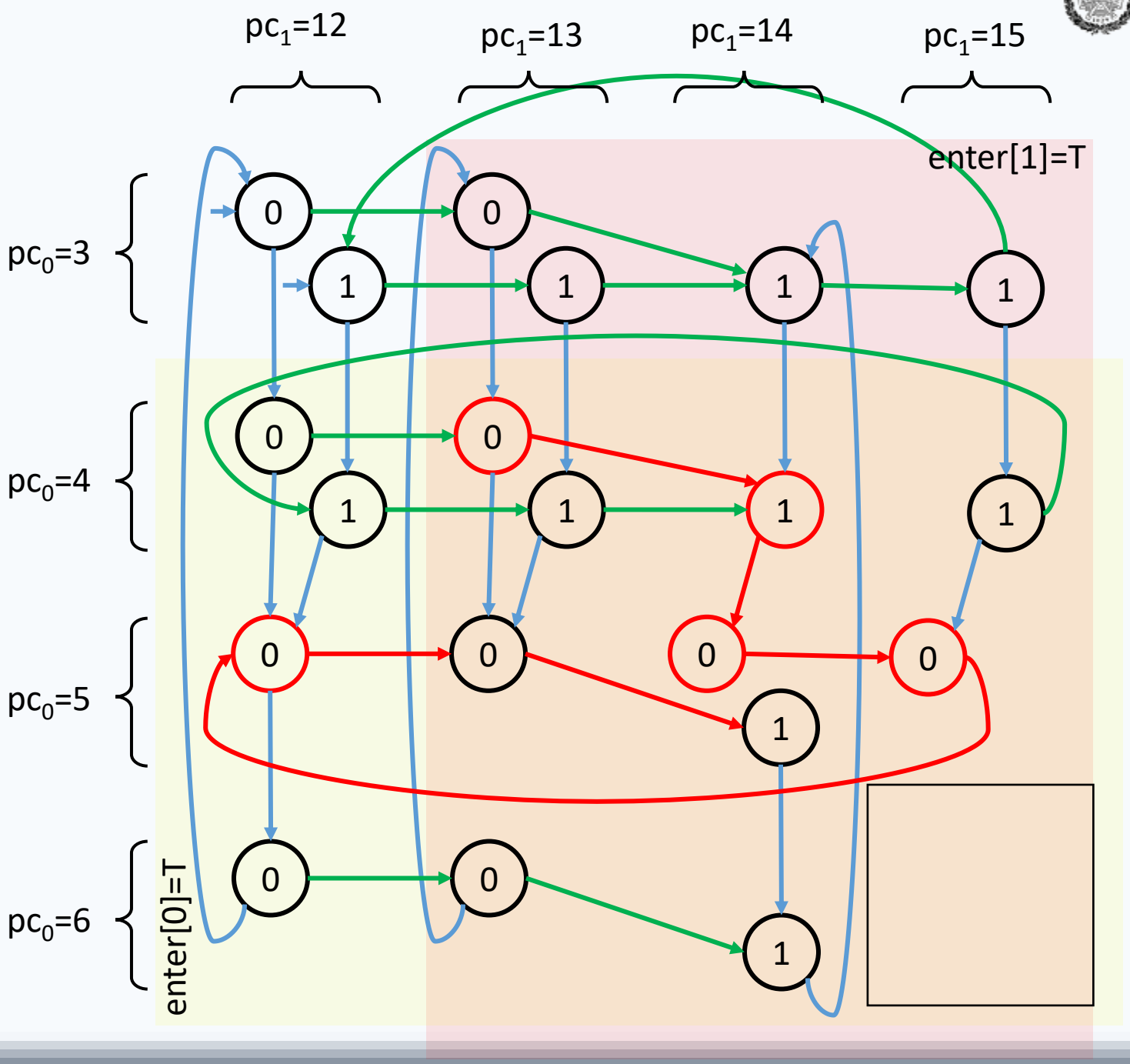


Peterson's algorithm is **starvation free**

(No thread keeps waiting to enter the critical section)

```
boolean[] enter = {false, false};   int yield = 0 || 1;
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	10
2	`  // entry protocol`	`  // entry protocol`	11
3	`  enter[0] = true;`	`  enter[1] = true;`	12
4	`  yield = 0;`	`  yield = 1;`	13
5	`  await (!enter[1] || yield != 0);`	`  await (!enter[0] || yield != 1);`	14
6	`  critical section { ... }`	`  critical section { ... }`	15
7	`  // exit protocol`	`  // exit protocol`	16
8	`  enter[0] = false;`	`  enter[1] = false;`	17
9	`}`	`}`	18

Peterson's algorithm satisfies **mutual exclusion**

Instead of building the state/transition diagram, we can also **prove mutual exclusion** by contradiction:

```
boolean[] enter = {false, false};   int yield = 0 || 1;
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	10
2	`  // entry protocol`	`  // entry protocol`	11
3	`  enter[0] = true;`	`  enter[1] = true;`	12
4	`  yield = 0;`	`  yield = 1;`	13
5	`  await (!enter[1] || yield != 0);`	`  await (!enter[0] || yield != 1);`	14
6	`  critical section { ... }`	`  critical section { ... }`	15
7	`  // exit protocol`	`  // exit protocol`	16
8	`  enter[0] = false;`	`  enter[1] = false;`	17
9	`}`	`}`	18

- Assume t_0 and t_1 both are in their critical section
- We have `enter[0] == true` and `enter[1] == true` (t_0 and t_1 set them before last entering their critical sections)
- Either `yield == 0` or `yield == 1`
  Without loss of generality, assume `yield == 0`
- Before last entering its critical section, t_0 must have set `yield` to `0`; after that it cannot have changed `yield` again
- To enter its critical section, t_0 must have read `yield == 1` (since `enter[1] == true`), so t_1 must have set `yield` to `1` after t_0 last changed `yield` to `0`
- Since neither thread can have changed `yield` to `0` after that, we must have `yield == 1`

Contradiction!

Peterson's algorithm is **starvation free**

Suppose t_0 is waiting to enter its critical section. At the same time, t_1 must be doing one of four things:

1. t_1 is in its critical section: then, it will eventually leave it;
2. t_1 is in its non-critical section: then, `enter[1] == false`, so t_0 can enter its critical section;
3. t_1 is waiting to enter its critical section: then, `yield` is either `0` or `1`, so one thread can enter the critical section;
4. t_1 keeps on entering and exiting its critical section: this is impossible because after t_1 sets `yield` to `1` it cannot cycle until t_0 has a chance to enter its critical section (and reset `yield`).

In all possible cases, t_0 eventually gets a chance to enter the critical section, so there is no starvation

Since starvation freedom implies deadlock freedom:

Peterson's algorithm is a correct mutual exclusion protocol

Peterson's algorithm is **starvation free**

```
boolean[] enter = {false, false};   int yield = 0 || 1;
```

thread t_0		thread t_1	
1	`while (true) {`	`while (true) {`	10
2	`// entry protocol`	`// entry protocol`	11
3	`enter[0] = true;`	`enter[1] = true;`	12
4	`yield = 0;`	`yield = 1;`	13
5	`await (!enter[1] || yield != 0);`	`await (!enter[0] || yield != 1);`	14
6	`critical section { ... }`	`critical section { ... }`	15
7	`// exit protocol`	`// exit protocol`	16
8	`enter[0] = false;`	`enter[1] = false;`	17
9	`}`	`}`	18

If `yield=0` (or `1`) and thread t_1 stops executing here (before the entry protocol)…

… then thread t_0 will **NOT starve** (it can go in into the critical section since enter[1]=false)

Peterson's algorithm for n threads

Peterson's algorithm easily generalizes to n threads

```
int[] enter = new int[n]; // n elements, initially all 0s
 int[] yield = new int[n]; // use n - 1 elements 1..n-1
```

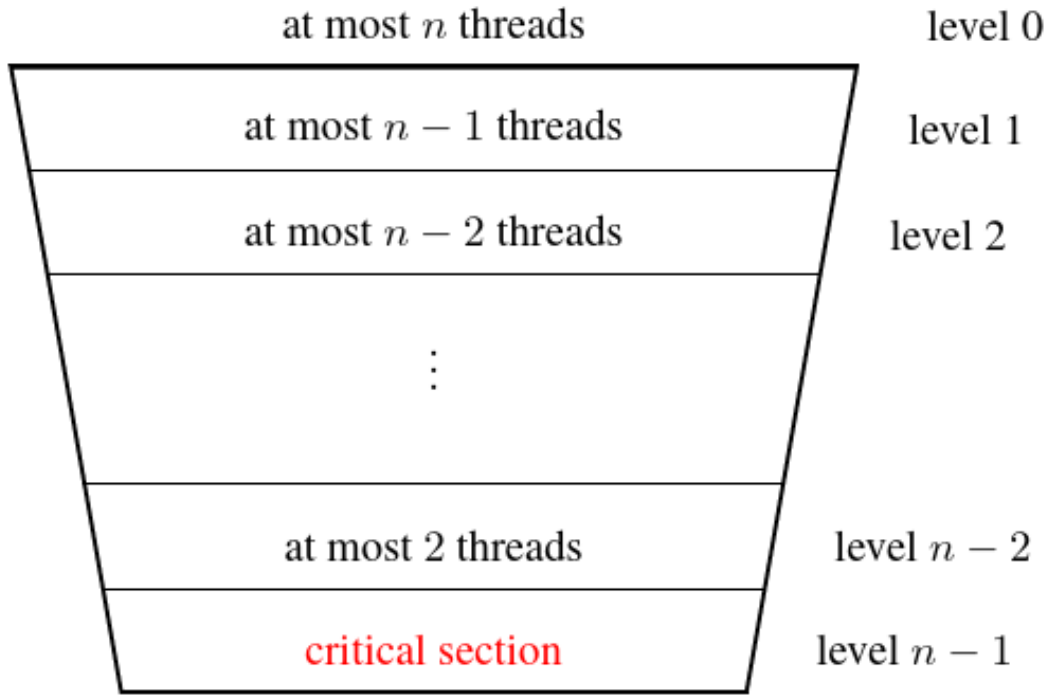
thread x

```
1  while (true) {
2   // entry protocol
3   for (int i = 1; i < n; i++) {
4     enter[x] = i;   // want to enter level i
5     yield[i] = x;   // but yield first
6     await (∀ t != x: enter[t] < i
                || yield[i] != x);
7   }
8   critical section { ... }
9   // exit protocol
10  enter[x] = 0;  // go back to level 0
```

wait until all other threads are in lower levels

or another thread is yielding

Peterson's algorithm for n threads




```
int[] enter = new int[n]; // n elements, initially all 0s
 int[] yield = new int[n]; // use n - 1 elements 1..n-1
```

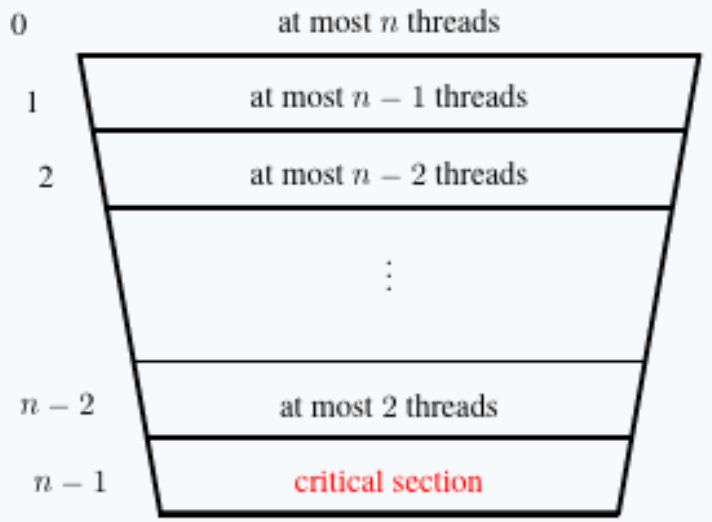
thread x

```
1  while (true) {
2   // entry protocol
3   for (int i = 1; i < n; i++) {
4     enter[x] = i;   // want to enter level i
5     yield[i] = x;   // but yield first
6     await (∀ t != x: enter[t] < i
                || yield[i] != x);
7   }
8   critical section { ... }
9   // exit protocol
10  enter[x] = 0;  // go back to level 0
```

Peterson's algorithm for n threads

Every thread goes through $n-1$ levels to enter the critical section:

- when a thread is at level 0 it is outside the entry region;
- when a thread is at level $n-1$ it is in the critical section;
- Thread `x` is in level `i` when it has finished the loop at line 6 with `enter[x]=i`;
- `yield[`ℓ`]` indicates the *last* thread that wants to enter level ℓ;
- to enter the next level, wait until there are no processes in higher levels, or another process (which entered the current level last) is yielding;
- mutual exclusion: at most $n-\ell$ processes are in level ℓ, thus at most $n-(n-1)=1$ processes in critical section.




```
int[] enter = new int[n]; // n elements, initially all 0s
int[] yield = new int[n]; // use n - 1 elements 1..n-1
```

thread x

```
1  while (true) {
2   // entry protocol
3   for (int i = 1; i < n; i++) {
4     enter[x] = i;   // want to enter level i
5     yield[i] = x;   // but yield first
6     await (∀ t != x: enter[t] < i
                || yield[i] != x);
7   }
8   critical section { ... }
9   // exit protocol
10  enter[x] = 0;  // go back to level 0
```

Mutual exclusion with bounded waiting

Bounded waiting (also called bounded bypass)

Peterson's algorithm guarantees freedom from starvation, but threads may get access to their critical section before other "older" threads

To describe this, we introduce more precise properties of fairness:

Finite waiting (starvation freedom): when a thread t is waiting to enter its critical section, it will eventually enter it

Bounded waiting: when a thread t is waiting to enter its critical section, the maximum number of times other arriving threads are allowed to enter their critical section before t is bounded by a function of the number of contending threads

r-bounded waiting: when a thread t is waiting to enter its critical section, the maximum number of times other arriving threads are allowed to enter their critical section before t is less than $r + 1$

First-come-first-served: 0-bounded waiting

The Bakery algorithm

Lamport's Bakery algorithm achieves mutual exclusion, deadlock freedom, and first-come-first-served access

It is based on the idea of waiting threads getting a ticket number:

- Because of lack of atomicity, two threads may end up with the same ticket number
- In that case, their thread identifier number is used to force an order
- The tricky part is evaluating multiple variables (the ticket numbers of all other waiting processes) consistently
- Idea: a thread raises a flag when computing the number; other threads then wait to compute the numbers

Main drawback (compared to Peterson's algorithm): the original version of the Bakery algorithm may use arbitrarily large integers (the ticket numbers) in shared variables

Implementing mutual exclusion algorithms in Java

Now that you know how to do it…

… don’t do it!

Learning how to achieve mutual exclusion using only atomic reads and writes has educational value, but you should not use it in realistic programs

- Use the locks and semaphores available in Java’s standard library
- We will still give an overview of the things to know if you were to implement Peterson’s algorithm, and similar ones, from the ground up

Peterson's lock in Java: 2 threads

```
class PetersonLock implements Lock {
    private volatile boolean enter0 = false, enter1 = false;
    private volatile int yield;

    public void lock()
    {   int me = getThreadId();
        if (me == 0) enter0 = true;
        else enter1 = true;
        yield = me;
        while ((me == 0) ? (enter1 && yield == 0)
                         : (enter0 && yield == 1)) {}   }

    public void unlock()
    {   int me = getThreadId();
        if (me == 0) enter0 = false;
        else enter1 = false;   }

    private volatile long id0 = 0;
```

volatile is required for correctness

The loop will exit:
if me=0 and (enter1 is false or yield is 1)
or
if me=1 and (enter0 is false or yield is 0)

Instruction execution order

When we designed and analyzed concurrent algorithms, we implicitly assumed that threads *execute instructions in textual program order*

This is not guaranteed by the Java language – or, for that matter, by most programming languages – when threads access shared fields

(Read "The silently shifting semicolon" http://drops.dagstuhl.de/opus/volltexte/2015/5025/ for a nice description of the problems)

- Compilers may reorder instructions based on static analysis, which does not know about threads.
- Processors may delay the effect of writes when the cache is committed to memory

This adds to the complications of writing low-level concurrent software correctly

Instruction execution order

The compiler might
Decide to move this instruction

```
class PetersonLock implements Lock {
    private volatile boolean enter0 = false, enter1 = false;
    private volatile int yield;

    public void lock()
    {   int me = getThreadId();
        if (me == 0) enter0 = true;
        else enter1 = true;
        yield = me;
        while ((me == 0) ? (enter1 && yield == 0)
                         : (enter0 && yield == 1)) {}  }

    public void unlock()
    {   int me = getThreadId();
        if (me == 0) enter0 = false;
        else enter1 = false;  }

    private volatile long id0 = 0;
```

- Compilers may reorder instructions based on static analysis, which does not know about threads.
- Processors may delay the effect of writes when the cache is committed to memory

This adds to the complications of writing low-level concurrent software correctly

Volatile fields

Accessing a field (attribute) declared as `volatile` forces synchronization, and thus prevents optimizations from reordering instructions in a way that alters the "happens before" relationship defined by a program's textual order

- By using `volatile` we ensure the variable changes at runtime and that the compiler should not cache its value for any reason

When accessing a shared variable that is accessed concurrently:

- declare the variable as `volatile`
- or guard access to the variable with locks (or other synchronization primitives)

Arrays and `volatile`

Java does **not support** arrays *whose elements* are `volatile`

That's why we used two scalar `boolean` var when implementating Peterson's lock

Workarounds:

- Use an object of class `AtomicIntegerArray` in package `java.util.concurrent.atomic` which guarantees atomicity of accesses to its elements (the field itself need not be declared volatile)
- Make sure that there is a read to a `volatile` field before every read to elements of the shared array, and that there is a write to a `volatile` field after every write to elements of the shared array; this forces synchronization indirectly (may be tricky to do correctly!)
- Explicitly guard accesses to shared arrays with a lock: this is the high-level solution which we will preferably use

Peterson's lock in Java: 2 threads, with atomic arrays

```
class PetersonAtomicLock implements Lock {
    private AtomicIntegerArray enter = new AtomicIntegerArray(2);
    private volatile int yield;

    public void lock() {
        int me = getThreadId();
        int other = 1 - me;
        enter.set(me, 1);
        yield = me;
        while (enter.get(other) == 1 && yield == me) {}
    }

    public void unlock() {
        int me = getThreadId();
        enter.set(me, 0);
    }
```

Peterson's lock in Java: 2 threads

”Classic”:

```
class PetersonLock implements Lock {
    private volatile boolean enter0 = false,
                             enter1 = false;
    private volatile int yield;

    public void lock()
    {   int me = getThreadId();
        if (me == 0) enter0 = true;
        else enter1 = true;
        yield = me;
        while ((me == 0) ? (enter1 && yield == 0)
                : (enter0 && yield == 1)) {}

    }

    public void unlock()
    {   int me = getThreadId();
        if (me == 0) enter0 = false;
        else enter1 = false;

    }
```

With atomic arrays:

```
class PetersonAtomicLock implements Lock {
    private AtomicIntegerArray
                enter = new AtomicIntegerArray(2);
    private volatile int yield;

    public void lock()
    {   int me = getThreadId();
        int other = 1 - me;
        enter.set(me, 1);
        yield = me;
        while (enter.get(other) == 1
                && yield == me) {}
    }

    public void unlock()
    {   int me = getThreadId();
        enter.set(me, 0);
    }
```

Mutual exclusion needs n memory locations

Peterson's algorithm for n **threads** uses $\Theta(n)$ shared memory locations (two n-element arrays)

- One can prove that this is the minimum amount of shared memory needed to have mutual exclusion *if only atomic reads and writes* are available
- This is one reason why synchronization using only atomic reads and writes is impractical

- We need more powerful primitive operations:
  - atomic test-and-set operations
  - support for suspending and resuming threads explicitly

Test-and-set

The test-and-set operation `boolean testAndSet()` works on a Boolean variable `b` as follows: `b.testAndSet()` atomically returns the current value of `b` and sets `b` to `true`

Java class `AtomicBoolean` implements test-and-set:

```
package java.util.concurrent.atomic;
public class AtomicBoolean {

 AtomicBoolean(boolean initialValue); // initialize to `initialValue'

 boolean get();                       // read current value
 void set(boolean newValue);          // write `newValue'

 // return current value and write `newValue'
 boolean getAndSet(boolean newValue);
                    // testAndSet() is equivalent to getAndSet(true)
}
```

A lock using test-and-set

An implementation of n-process mutual exclusion using a single Boolean variable with test-and-set and busy waiting:

```
public class TASLock implements Lock {
  AtomicBoolean held =
                new AtomicBoolean(false);

  public void lock() {
    while (held.getAndSet(true)) {
    }  // await (!testAndSet());
  }

  public void unlock() {
    held.set(false); // held = false;
  }
}
```

- Variable `held` is true iff the lock is held by some thread
- When locking (executing `lock`):
  - as long as `held` is true (someone else holds the lock), keep resetting it to true and wait
  - as soon as `held` is false: leave the loop and `held` is set it to true
    - You hold the lock now
- When unlocking (executing `unlock`): set `held` to false

A lock using test-and-test-and-set

A lock implementation using a single Boolean variable with test-and-test-and-set and busy waiting:

```
public class TTASLock extends TASLock {
  @Override
  public void lock() {
    while (true) {
      while(held.get()) {}
      if (!held.getAndSet(true))
        return;
    }
  }
}
```

When locking (executing `lock`):

- spin until `held` is false
- then check if `held` is still false, and if it is set it to true (you hold the lock now), then return
- otherwise it means another thread "stole" the lock from you; then repeat the locking procedure from the beginning

This variant tends to *perform better*, since the busy waiting is local to the cached copy as long as no other thread changes the lock's state (Read section 7.2 of Herlihy and Shavit book)

Implementing semaphores

Semaphores: recap

A (general/counting) semaphore is a data structure with interface:

```
interface Semaphore {
  int count();    // current value of counter
  void up();      // increment counter
  void down();    // decrement counter
}
```

Several threads share the same object `sem` of type `Semaphore`:

- initially `count` is set to a nonnegative value `C` (the initial capacity)
- a call to `sem.up()` ***atomically*** increments `count` by one
- a call to `sem.down()`: ***waits*** until `count` is positive, and then ***atomically*** decrements `count` by one

Semaphores with locks

An implementation of semaphores using locks and busy waiting:

```
class SemaphoreBusy implements Semaphore {
    private int count;

    public synchronized void up() {
       count = count + 1;
    }

    public void down() {
       while (true) {
          synchronized (this) {
             if (count > 0) { // await (count > 0);
                   count = count - 1; return;
             }
          }
       }
    }

    public synchronized int count() {
       return count;
    }
}
```

Executed exclusively

Why not lock the whole method?

To avoid blocking other threads to enter the method (avoid that the first thread calling `down` is the first to get the lock!)

Does this have to be **`synchronized`**?

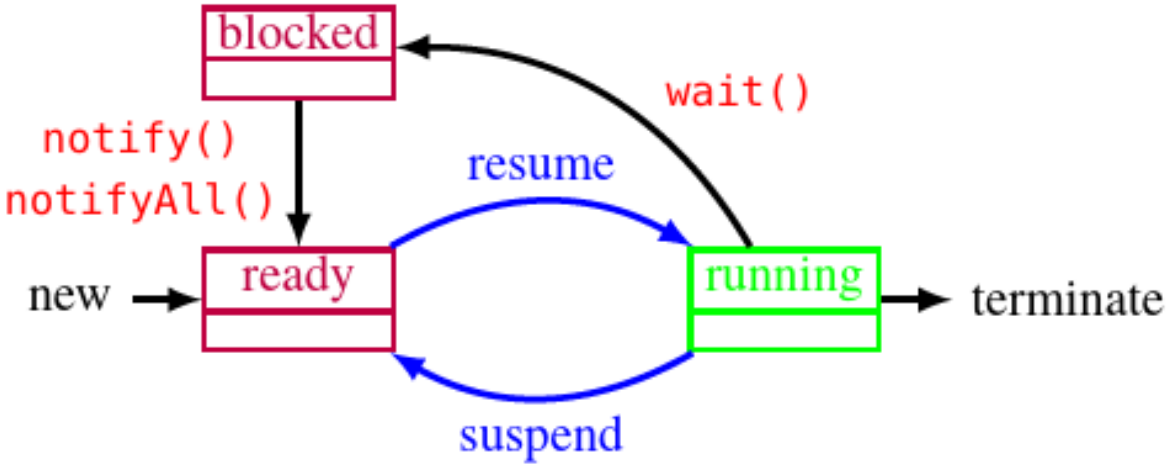
Yes, if `count` is not **`volatile`**

Suspending and resuming threads

To avoid busy waiting, we have to rely on more powerful synchronization primitives than only reading and writing variables

A standard solution uses Java's explicit scheduling of threads

- calling `wait()` suspends the currently running thread
- calling `notify()` moves one (nondeterministically chosen) blocked thread to the ready state
- calling `notifyAll()` moves all blocked threads to the ready state



Waiting and notifying only affects the threads that are locked on the same shared object (using **`synchronized`** blocks or methods)

Weak semaphores with suspend/resume

An implementation of weak semaphores using `wait()` and `notify()`

```
class SemaphoreWeak implements Semaphore {
    private int count;

    public synchronized void up() {
        count = count + 1;
        notify();      // wake up a waiting thread
    }

    public synchronized void down() throws InterruptedException {
        while (count == 0)  wait();  // suspend running thread
        count = count - 1;           // now count > 0
    }

    public synchronized int count() {
        return count;
    }
}
```

Since `notify` is nondeterministic this is a **weak** semaphore

`wait` releases the object lock (so other threads can enter the method even if it is marked as "synchronized")

In general, `wait` must be called in a loop in case of spurious wakeups; this is not busy waiting (and it's required by Java's implementation)

Strong semaphores with suspend/resume

An implementation of strong semaphores using `wait()` and `notifyAll()`

```
class SemaphoreStrong implements Semaphore {

    public synchronized void up() {
      if (blocked.isEmpty()) count = count + 1;
      else notifyAll();       // wake up all waiting threads
     }

    public synchronized void down() throws InterruptedException {
        Thread me = Thread.currentThread();
        blocked.add(me);   // enqueue me
        while (count == 0 || blocked.element() != me)
            wait();              // I'm enqueued when suspending
        // now count > 0 and it's my turn: dequeue me and decrement
        blocked.remove();  count = count - 1;
    }

    private final Queue<Thread> blocked = new LinkedList<>();

    private int count;
```

Check there are no suspended threads

Wrong!

Keeps suspending the thread if the count is 0 or I am not the first in the queue

Strong semaphores with suspend/resume

An implementation of strong semaphores using `wait()` and `notifyAll()`

```
class SemaphoreStrong implements Semaphore {

    public synchronized void up() {
        count = count + 1;
        notifyAll();      // wake up all waiting threads
    }

    public synchronized void down() throws InterruptedException {
        Thread me = Thread.currentThread();
        blocked.add(me);  // enqueue me
        while (count == 0 || blocked.element() != me)
            wait();           // I'm enqueued when suspending
        // now count > 0 and it's my turn: dequeue me and decrement
        blocked.remove();  count = count - 1;

    }

    private final Queue<Thread> blocked = new LinkedList<>();

    private int count;
}
```

Removed `if (blocked.isEmpty())`


Debugging concurrent programs is very difficult!

General semaphores using binary semaphores

A general semaphore can be implemented using just two binary semaphores

Barz's solution in *pseudocode* (with `capacity` > 0):

```
BinarySemaphore mutex = 1; // protects access to count
BinarySemaphore delay = 1; // blocks threads in down until count >0
int count = capacity;      // value of general semaphore
void up()
{  mutex.down();                  // get exclusive access to count
   count = count + 1;             // increment count
   if (count == 1) delay.up();    // release threads blocking on down
   mutex.up(); }                  // release exclusive access to count
void down()
{ delay.down();                   // block other threads starting down
  mutex.down();                   // get exclusive access to count
  count = count - 1;              // decrement count
  if (count > 0) delay.up();      // release threads blocking on down
  mutex.up(); }                   // release exclusive access to count
```

```
1  class SemaphoreStrong implements Semaphore {
2      public synchronized void up()
3      {   if (blocked.isEmpty()) count = count + 1;
4          else notifyAll();    } // wake up all waiting threads
5
6      public synchronized void down() throws InterruptedException
7      {   Thread me = Thread.currentThread();
8          blocked.add(me);  // enqueue me
9          while (count == 0 || blocked.element() != me)
10             wait();         // I'm enqueued when suspending
11         // now count > 0 and it's my turn: dequeue me and decrement
12         blocked.remove();  count = count - 1;   }
13
14     private final Queue<Thread> blocked = new LinkedList<>();
```

```
15 class StrongSemUser implements Runnable {
16     private SemaphoreStrong sem = new SemaphoreStrong(1);
17
18     public void run()
19     {    while (true) {
20             // Non critical
21             sem.down();
22             // Critical
23             sem.up();
24         }
25     }
```

```
class StrongSemUser implements Runnable {
    private SemaphoreStrong sem = new SemaphoreString(1);

    public void run()
    {   while (true) {
            // Non critical
            sem.down();
            // Critical
            sem.up();
        }
    }
```

Peterson's algorithm

Combine the ideas behind the second and third attempts:

- thread t_k first sets `enter[k]` to true
- but lets the other thread go first – by setting `yield`

Equivalent to: wait while (enter[1]=true & yield=0)

Enter only when (enter[1]=false OR yield=1)

Works even if two reads are non-atomic

```
boolean[] enter = {false, false};   int yield = 0 || 1;
        thread t0                           thread t1
1  while (true) {                  10 while (true) {
2    // entry protocol             11   // entry protocol
3    enter[0] = true;             12   enter[1] = true;
4    yield = 0;                   13   yield = 1;
5    await (!enter[1]     ||      14   await (!enter[0]     ||
           yield != 0);                      yield != 1);
6    critical section { ... }     15 critical section { ... }
7    // exit protocol             16 // exit protocol
8    enter[0] = false;            17 enter[1] = false;
9  }                              18 }
```


Peterson's algorithm for n threads

Peterson's algorithm easily generalizes to n threads

```
int[] enter = new int[n]; // n elements, initially all 0s
int[] yield = new int[n]; // use n - 1 elements 1..n-1
                thread x
1  while (true) {
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10   enter[x] = 0;  // go back to level 0
```

wait until all other threads are in lower levels

or another thread is yielding

Peterson's lock in Java: 2 threads

```
class PetersonLock implements Lock {
    private volatile boolean enter0 = false, enter1 = false;
    private volatile int yield;

    public void lock()
    {   int me = getThreadId();
        if (me == 0) enter0 = true;
        else enter1 = true;
        yield = me;
        while ((me == 0) ? (enter1 && yield == 0)
                         : (enter0 && yield == 1)) {}  }

    public void unlock()
    {   int me = getThreadId();
        if (me == 0) enter0 = false;
        else enter1 = false;  }

    private volatile long id0 = 0;
```

volatile is required for correctness

The loop will exit: if me=0 and (enter1 is false or yield is 1) or if me=1 and (enter0 is false or yield is 0)

Instruction execution order

When we designed and analyzed concurrent algorithms, we implicitly assumed that threads *execute instructions in textual program order*

This is not guaranteed by the Java language – or, for that matter, by most programming languages – when threads access shared fields

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This adds to the complications of writing low-level concurrent software correctly

Peterson's lock in Java: 2 threads, with atomic arrays

```
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    private AtomicIntegerArray enter = new AtomicIntegerArray(2);
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    public void lock() {
        int me = getThreadId();
        int other = 1 - me;
        enter.set(me, 1);
        yield = me;
        while (enter.get(other) == 1 && yield == me) {}
    }

    public void unlock() {
        int me = getThreadId();
        enter.set(me, 0);
    }
```


Test-and-set

The test-and-set operation `boolean testAndSet()` works on a Boolean variable `b` as follows: `b.testAndSet()` atomically returns the current value of `b` and sets `b` to `true`

Java class `AtomicBoolean` implements test-and-set:

```
package java.util.concurrent.atomic;
public class AtomicBoolean {

  AtomicBoolean(boolean initialValue); // initialize to 'initialValue'

  boolean get();                       // read current value
  void set(boolean newValue);          // write 'newValue'

  // return current value and write 'newValue'
  boolean getAndSet(boolean newValue);
                  // testAndSet() is equivalent to getAndSet(true)
}
```