Synchronization: Implementing Barriers Promises + Futures

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CS378

Today

- Questions?
- Administrivia
    - Lab 2 due sooner than you'd like
- Material for the day
    - Barrier implementation
    - Promises & Futures

- Acknowledgements
    - Thanks to Gadi Taubenfield: I borrowed from some of his slides on barriers

Faux Quiz (answer any N, 5 min)

- How are promises and futures related? Since there is disagreement on the nomenclature, don’t worry about which is which—just describe what the different objects are and how they function.

Barriers

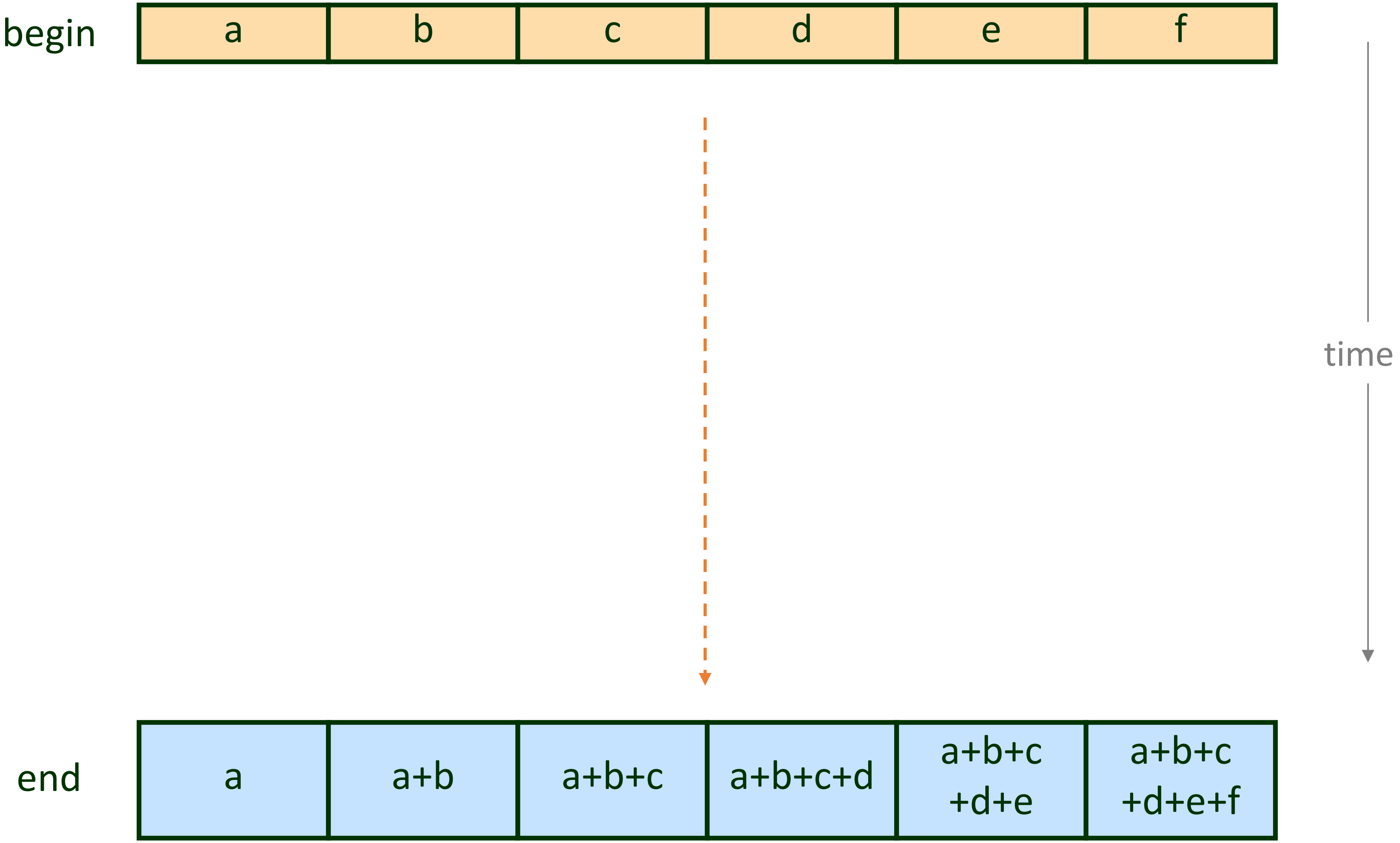
Barriers

Prefix Sum

Prefix Sum

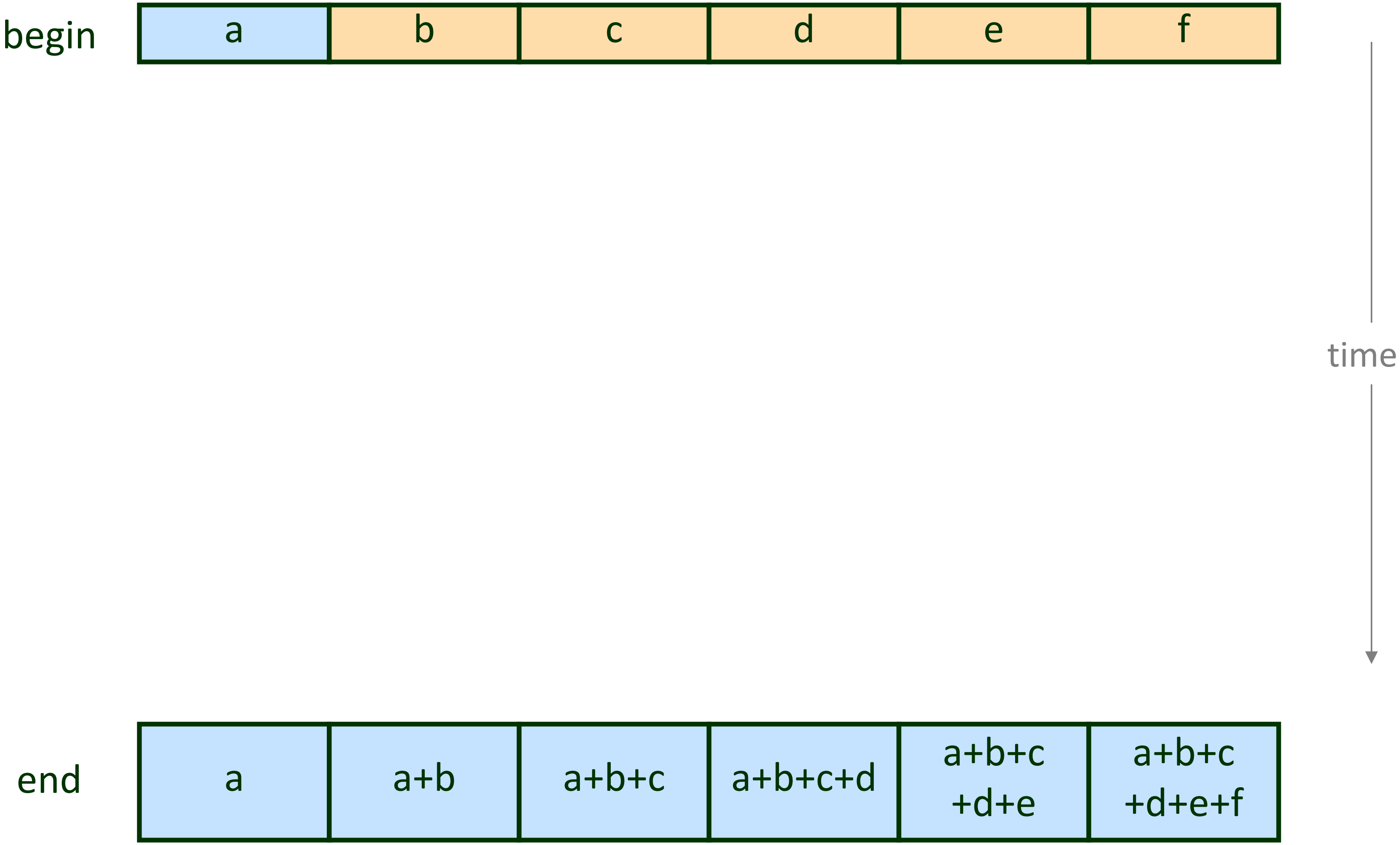
begin	a	b	c	d	e	f

Prefix Sum



begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum

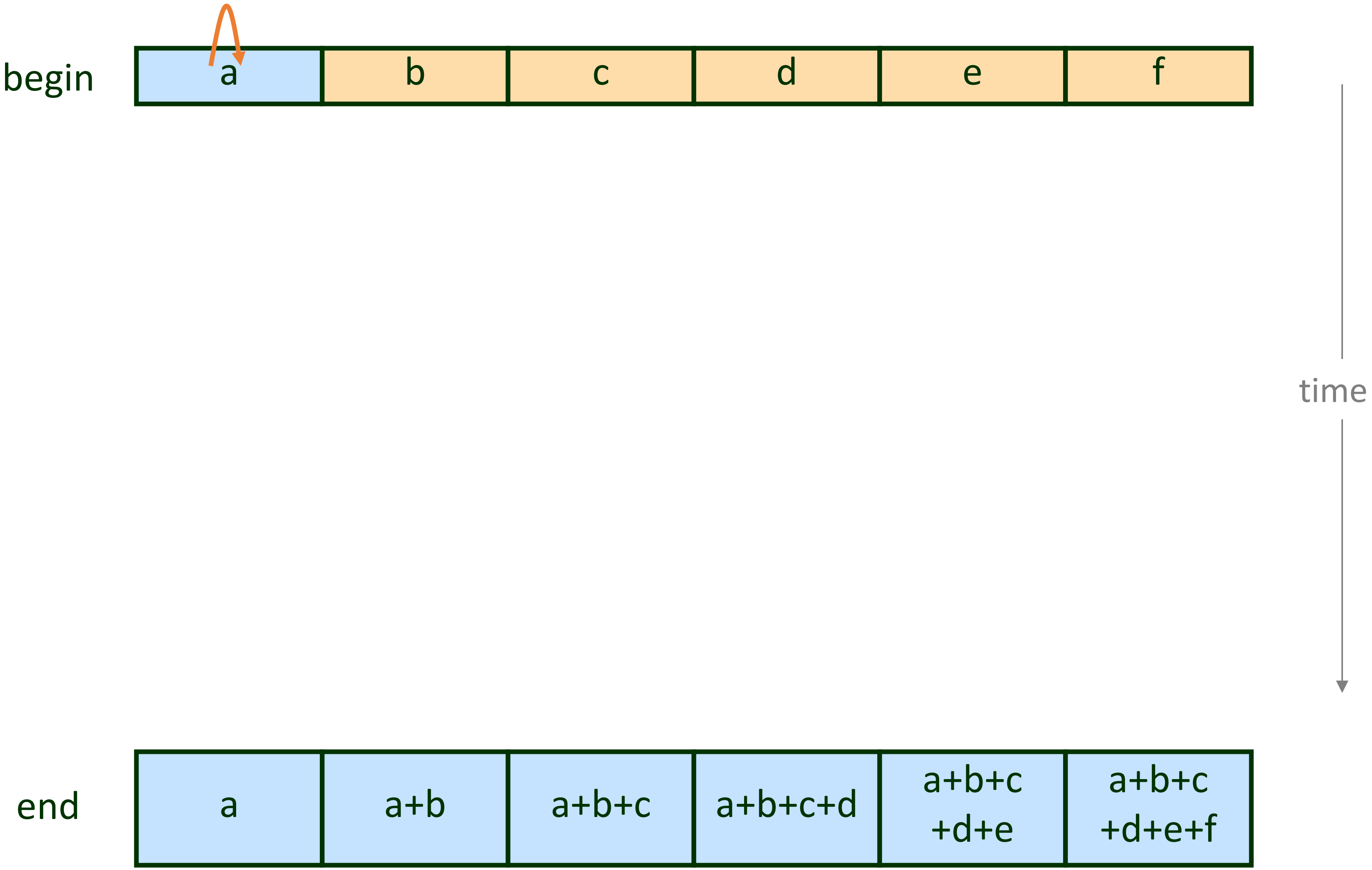


begin	a	b	c	d	e	f

time

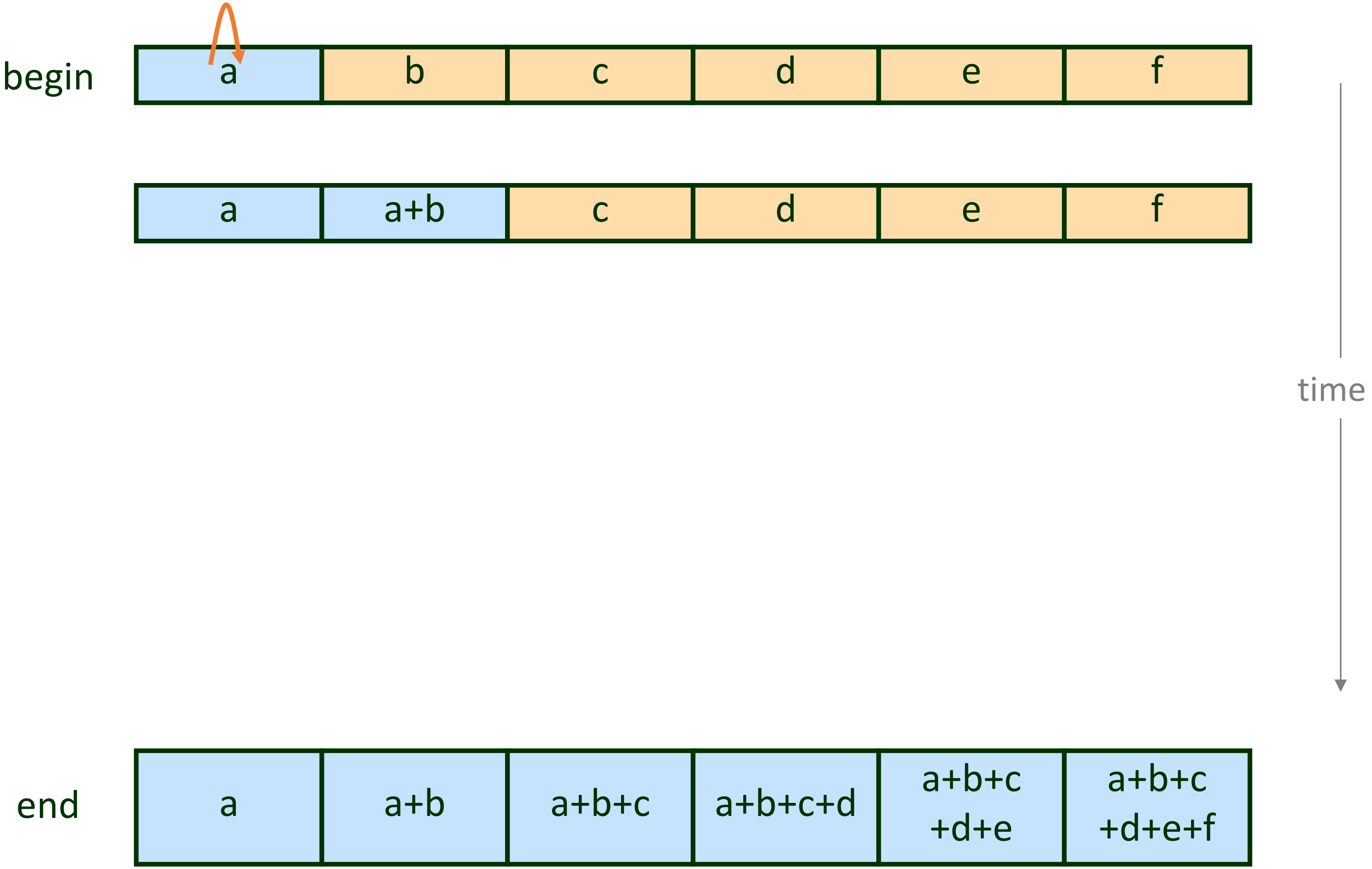
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin

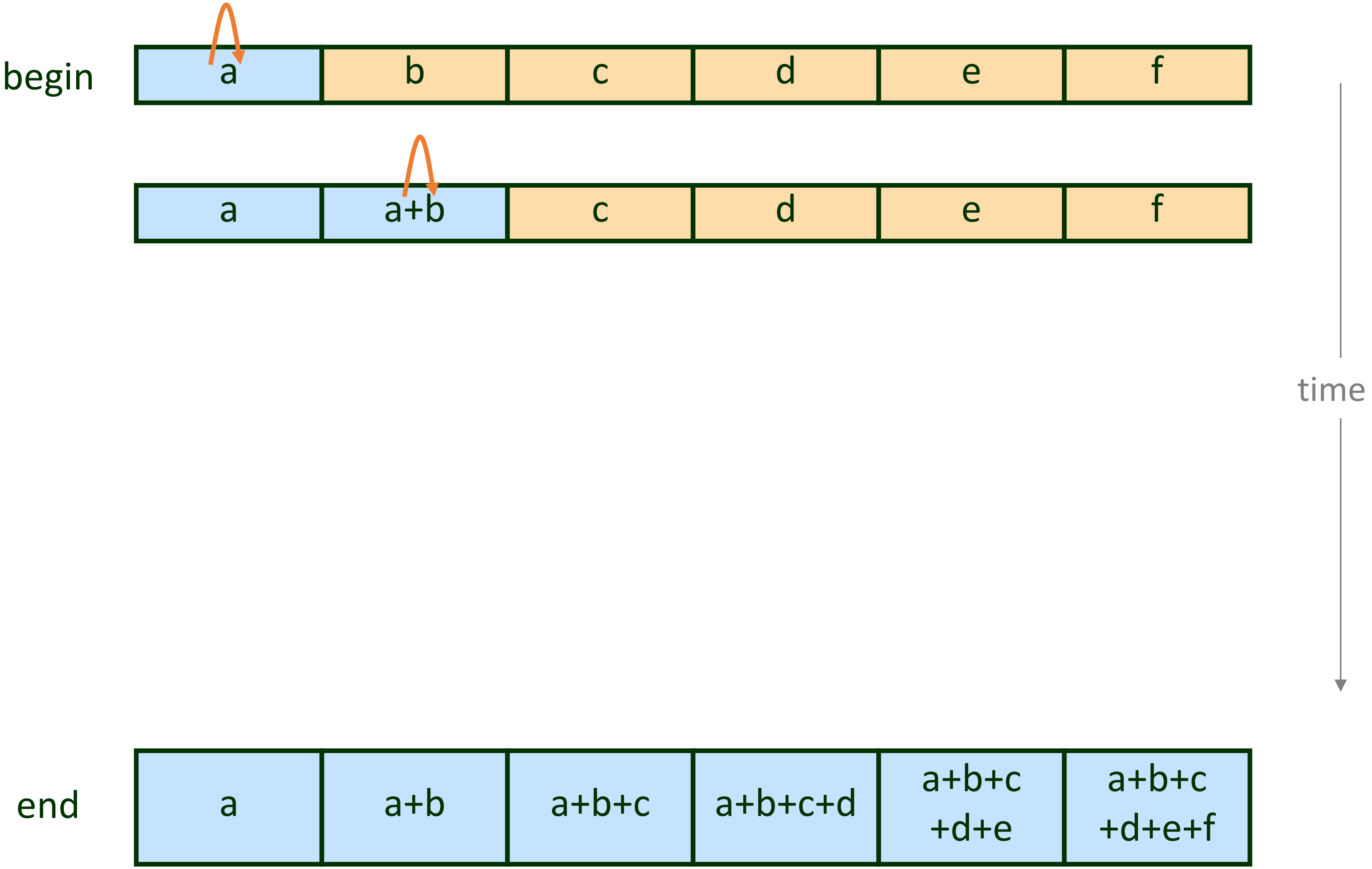
a	b	c	d	e	f

a	a+b	c	d	e	f

end

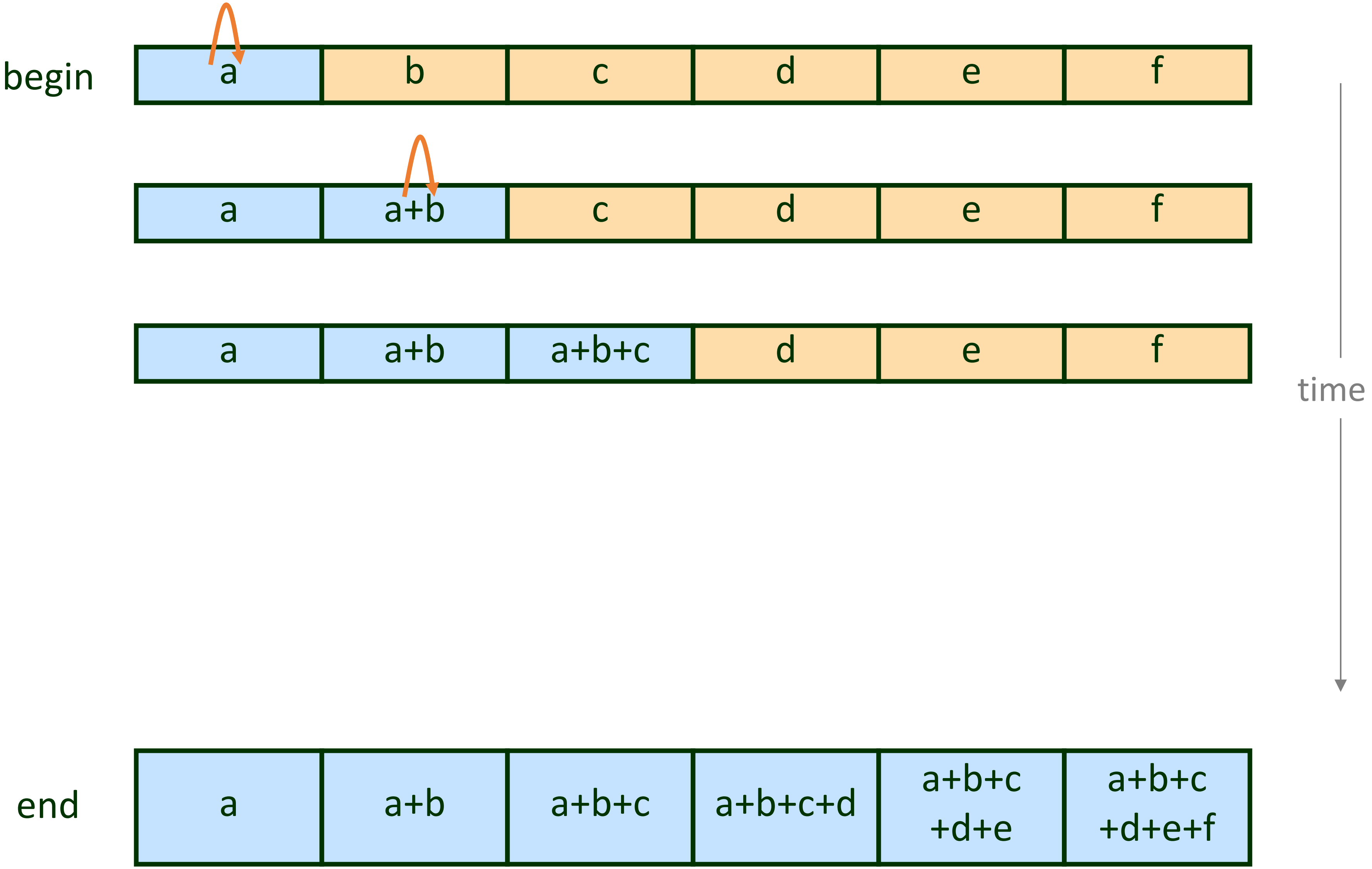
a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
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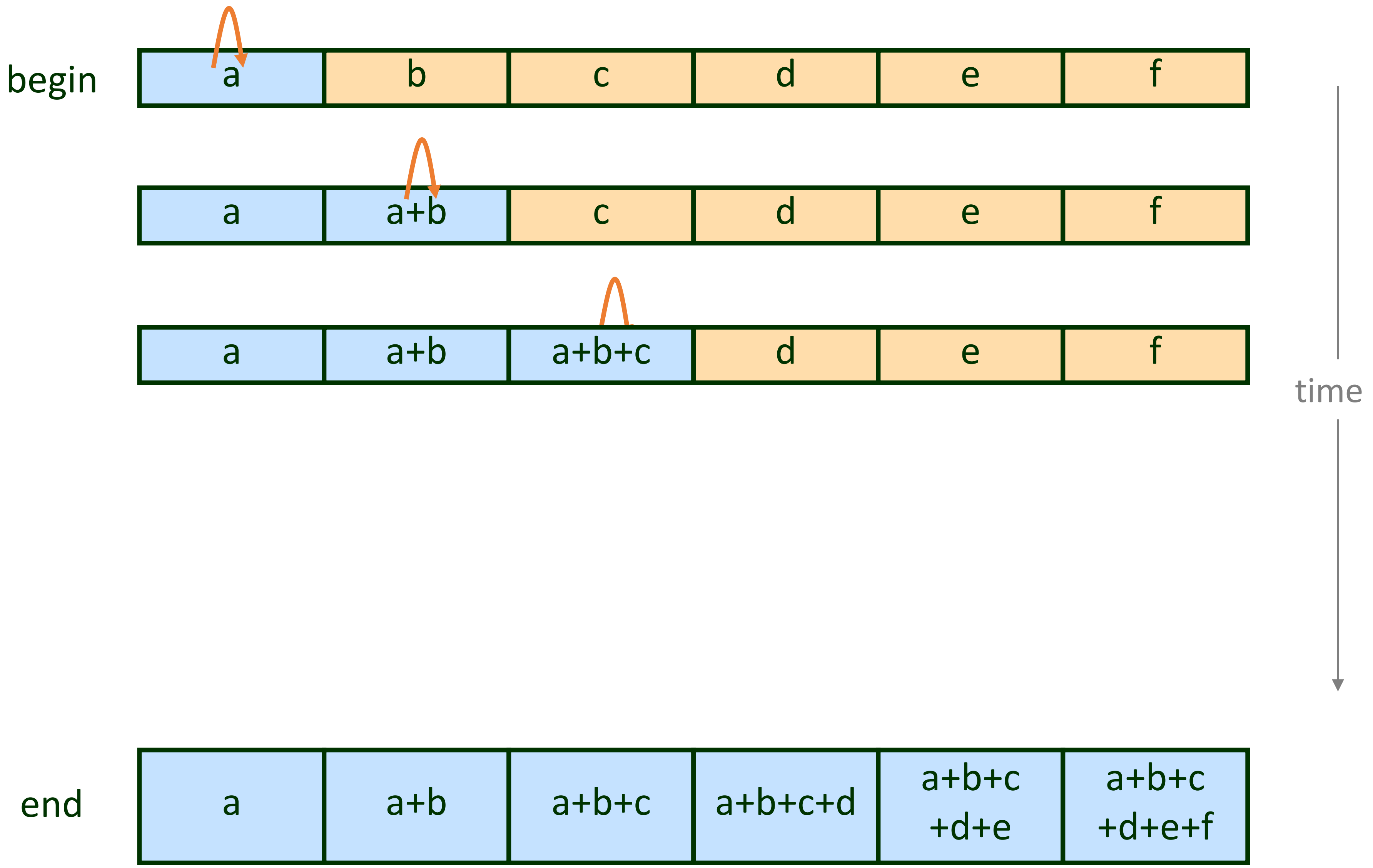
Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

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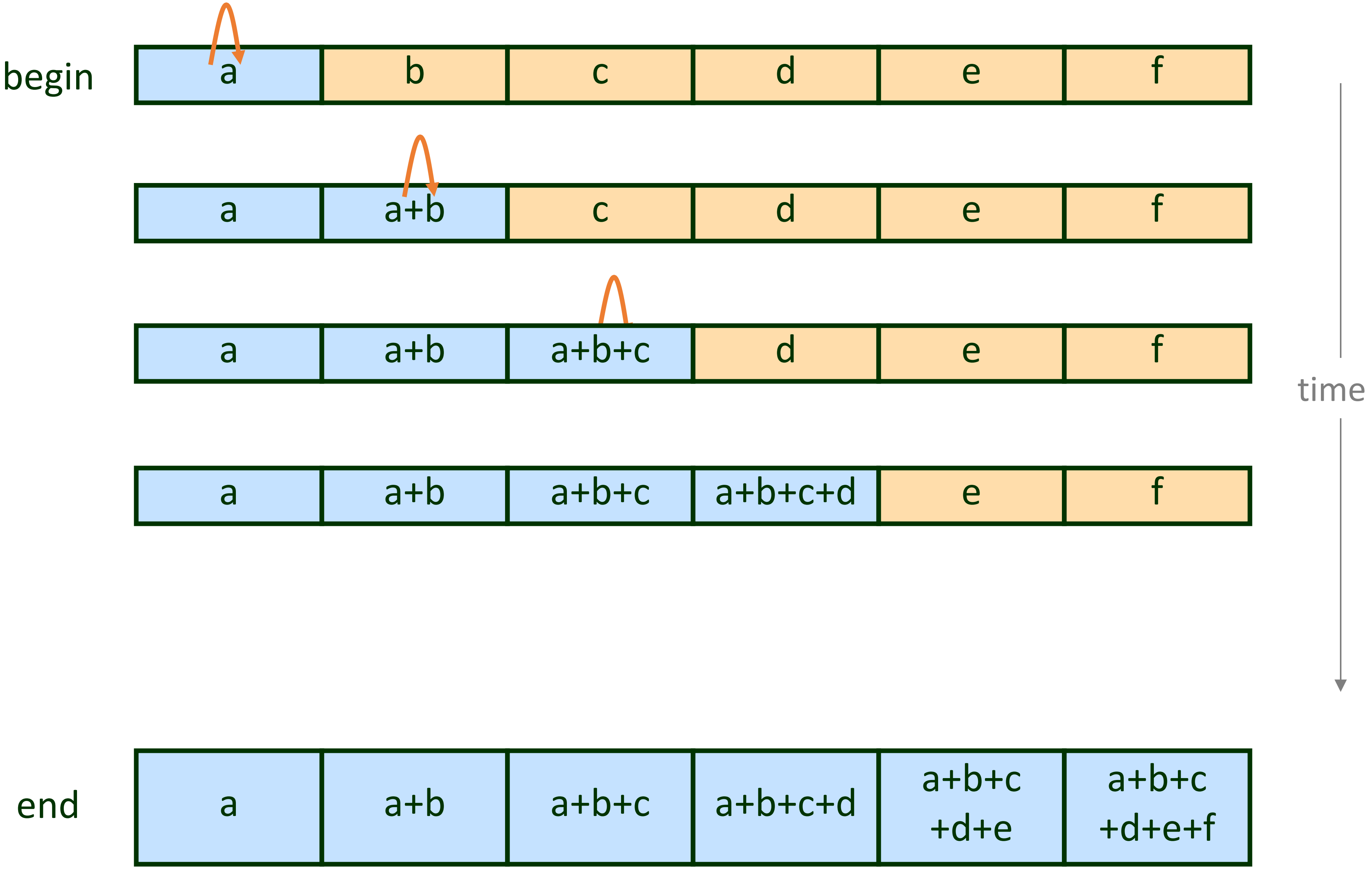
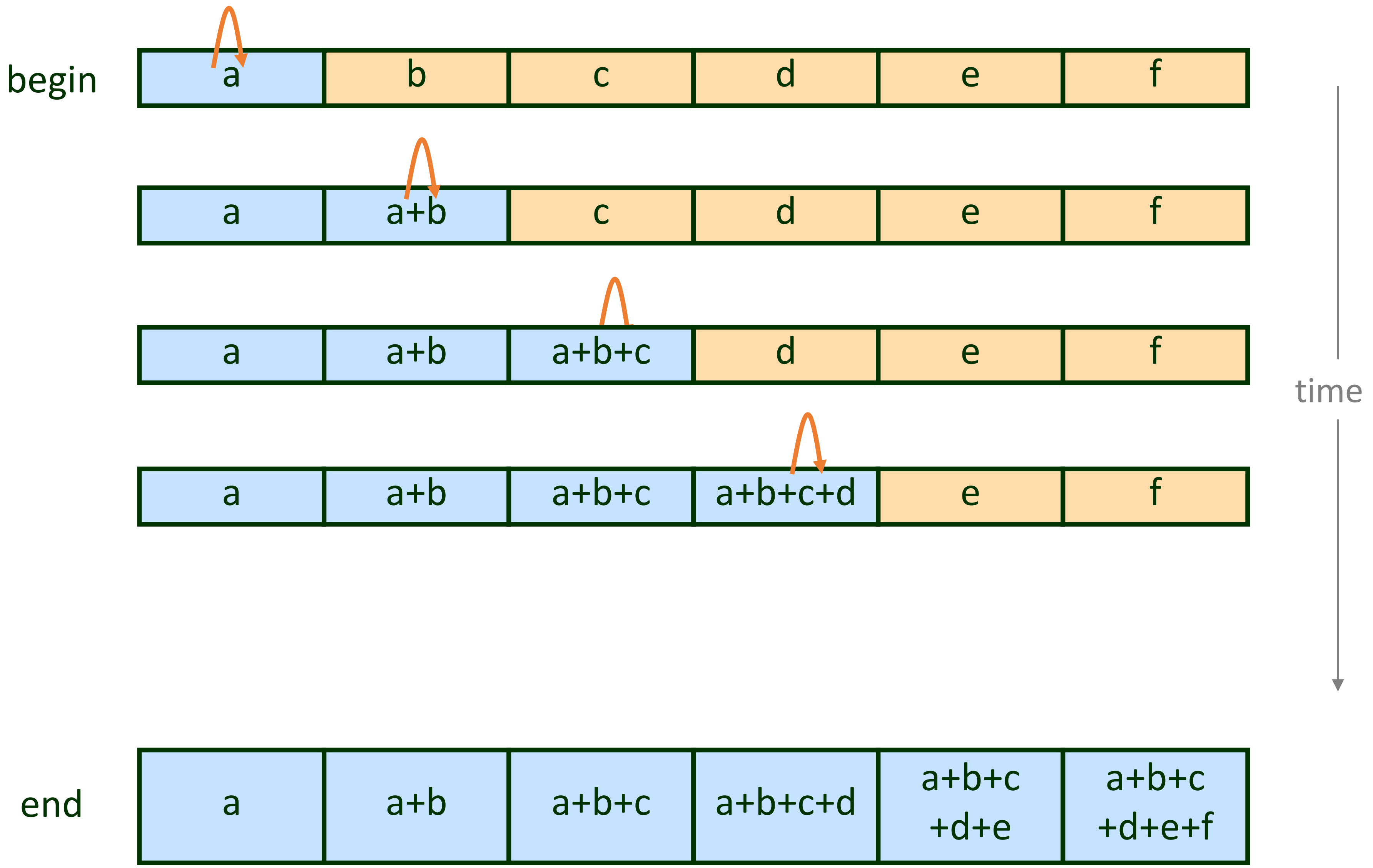


begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

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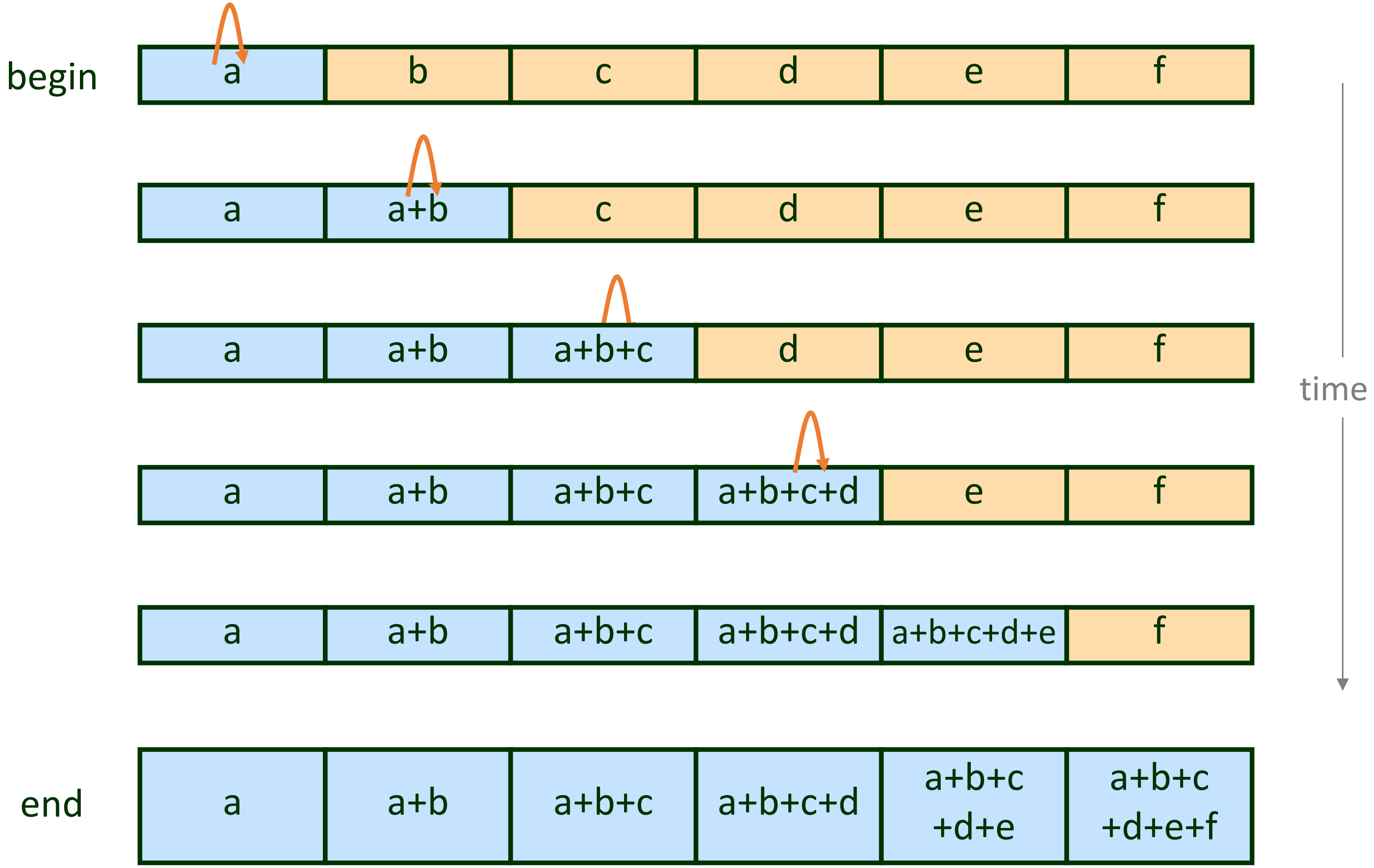

begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
	a	a+b	a+b+c	a+b+c+d	a+b+c+d+e	f
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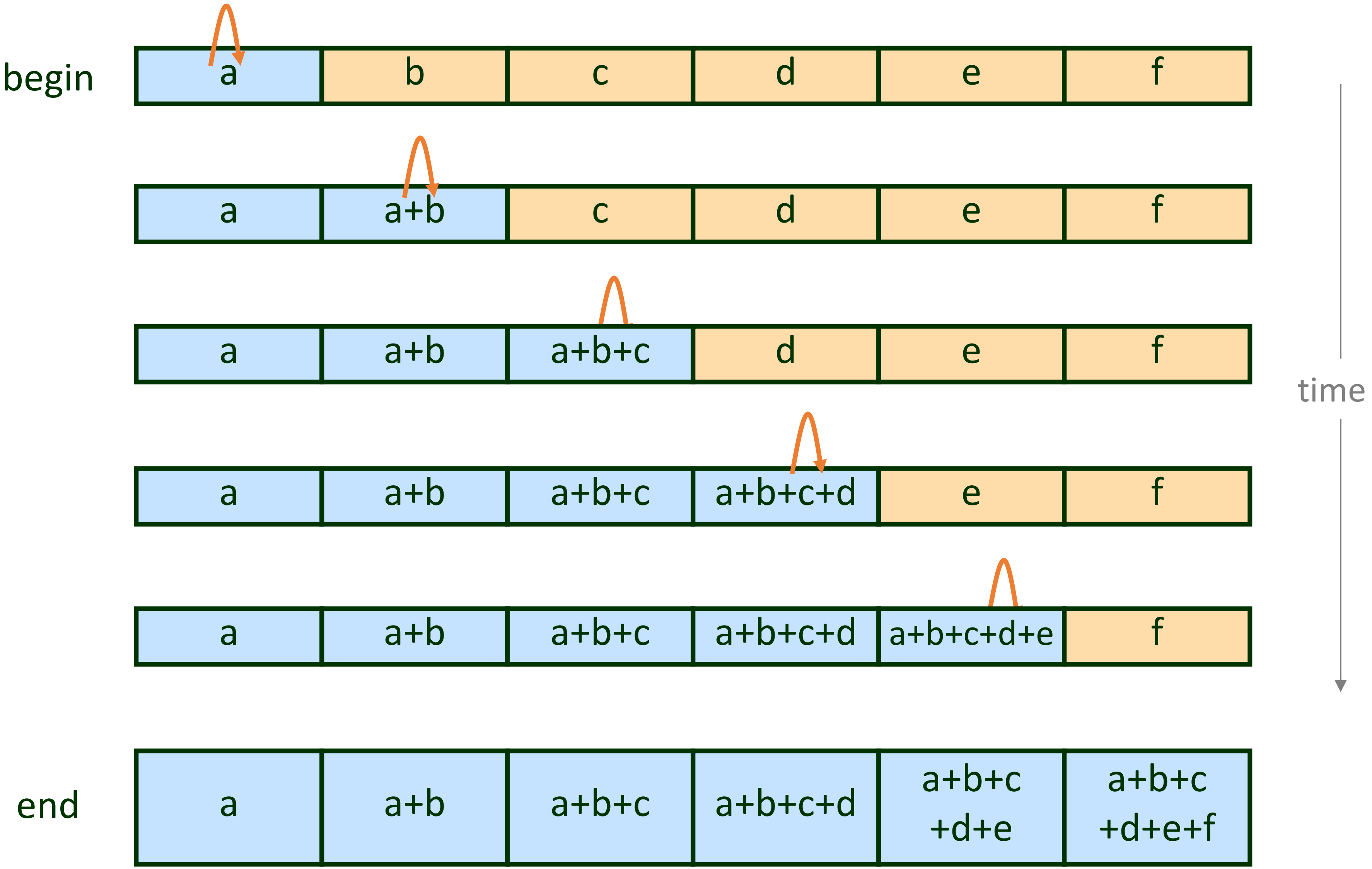
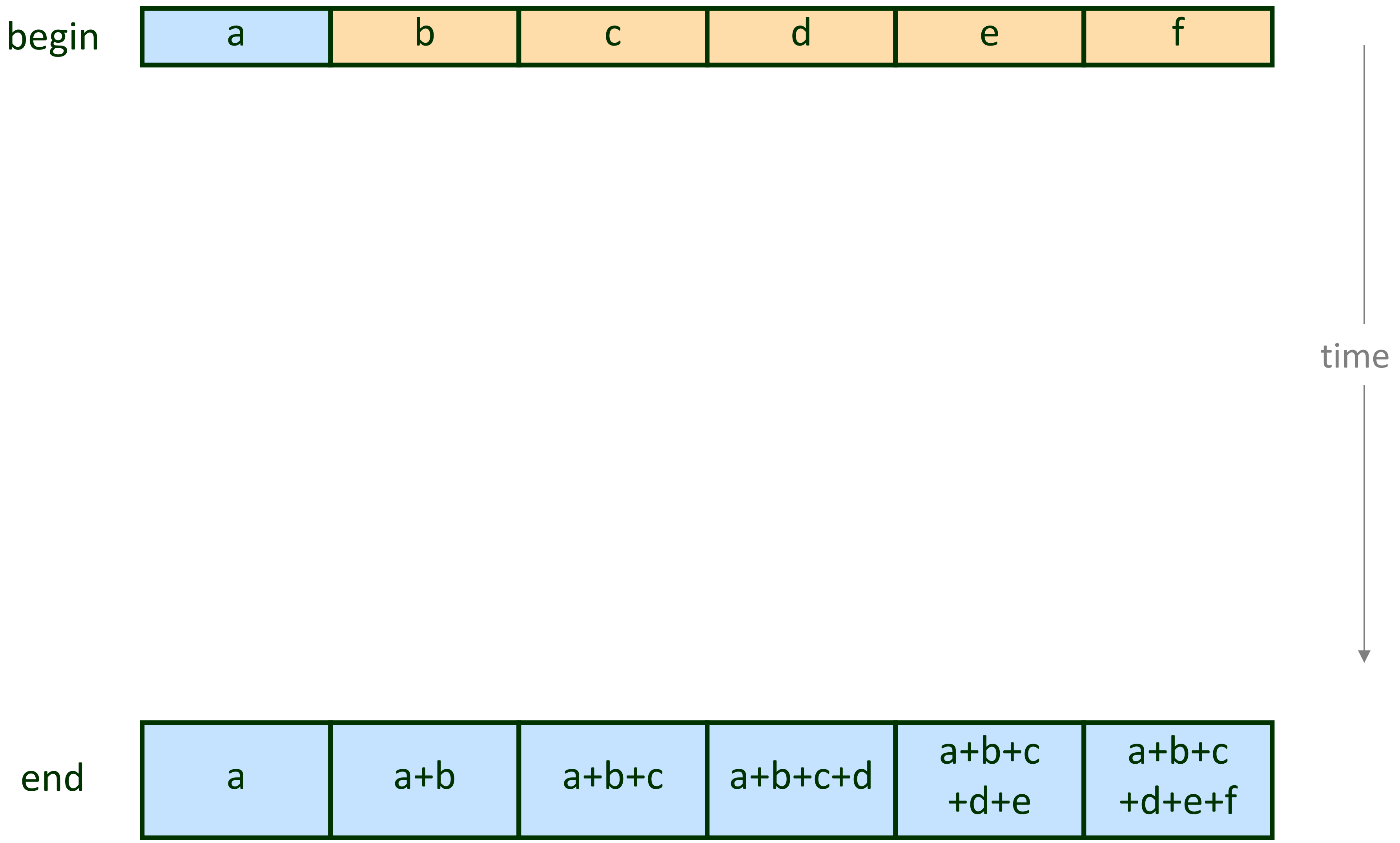


begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
	a	a+b	a+b+c	a+b+c+d	a+b+c+d+e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum



begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

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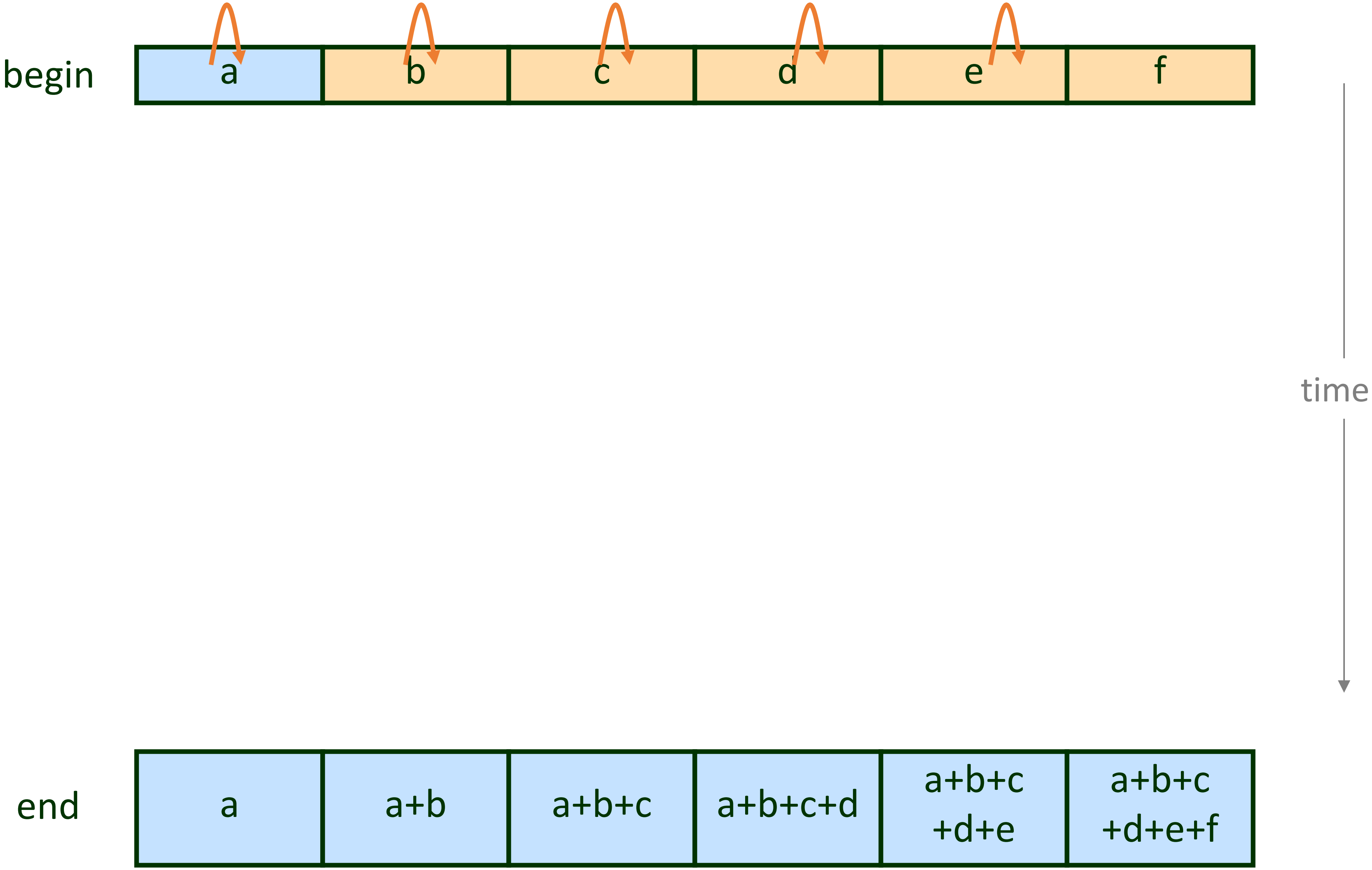

begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

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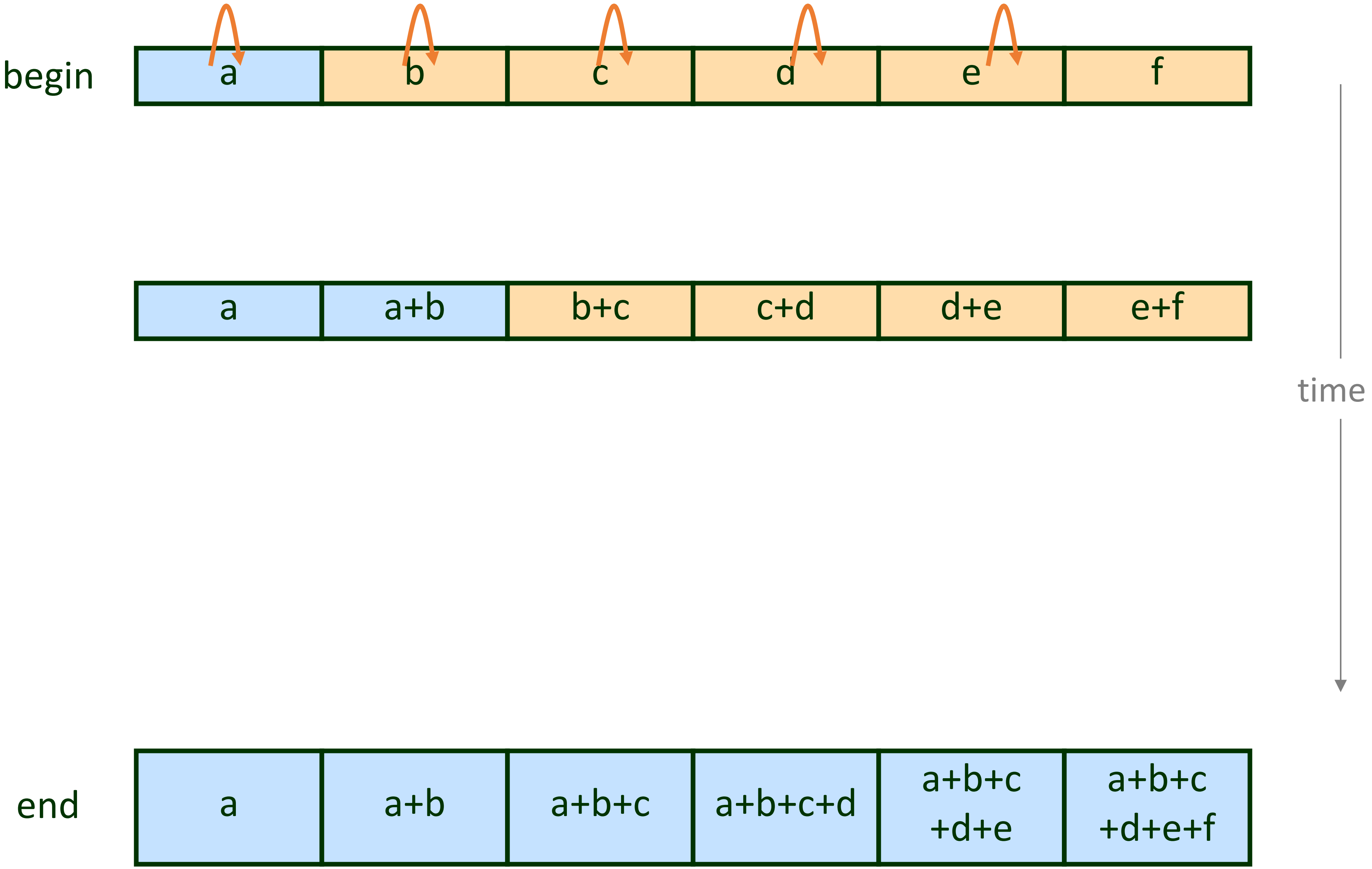
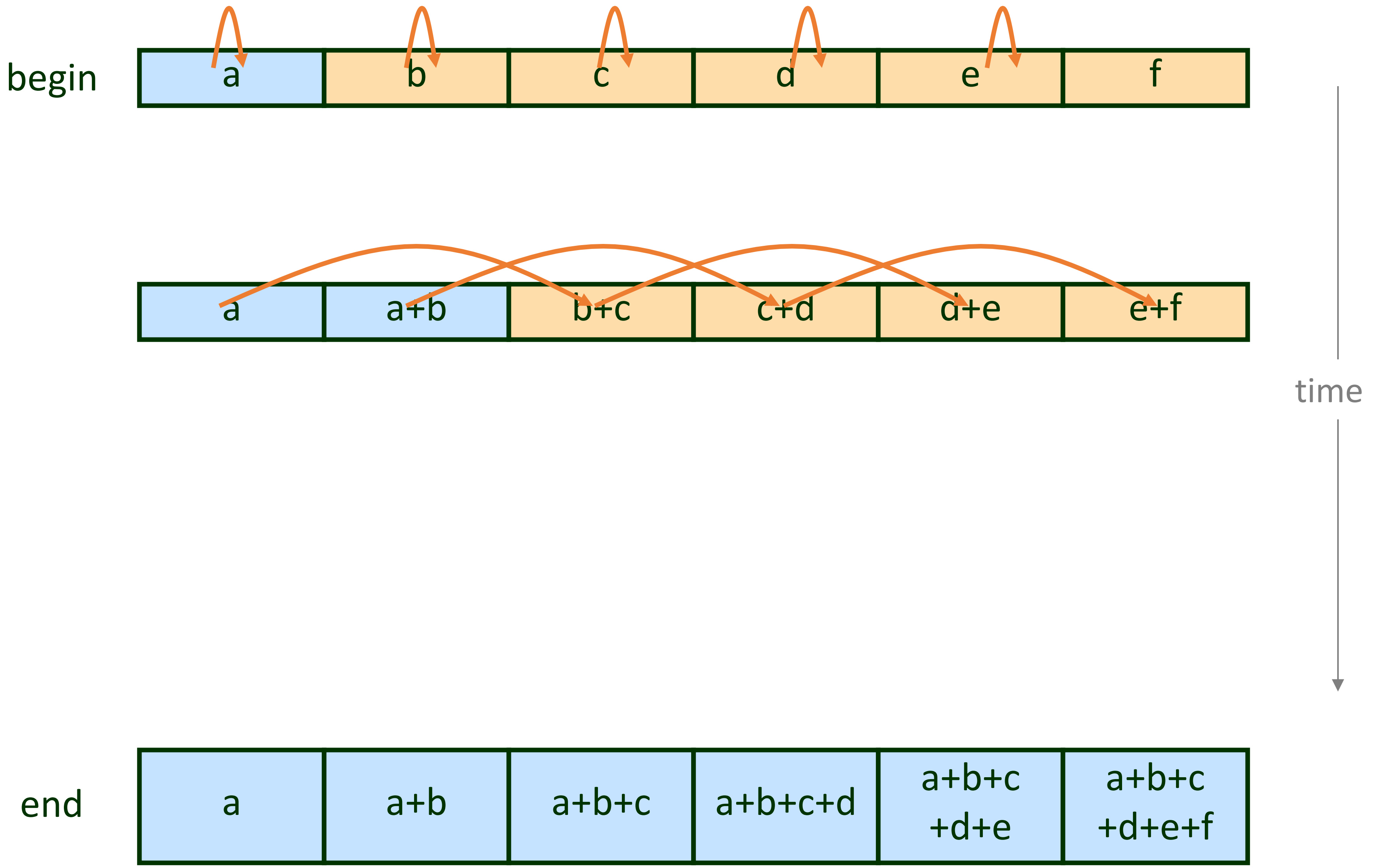


begin	a	b	c	d	e	f
	a	a+b	b+c	c+d	d+e	e+f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	b+c	c+d	d+e	e+f
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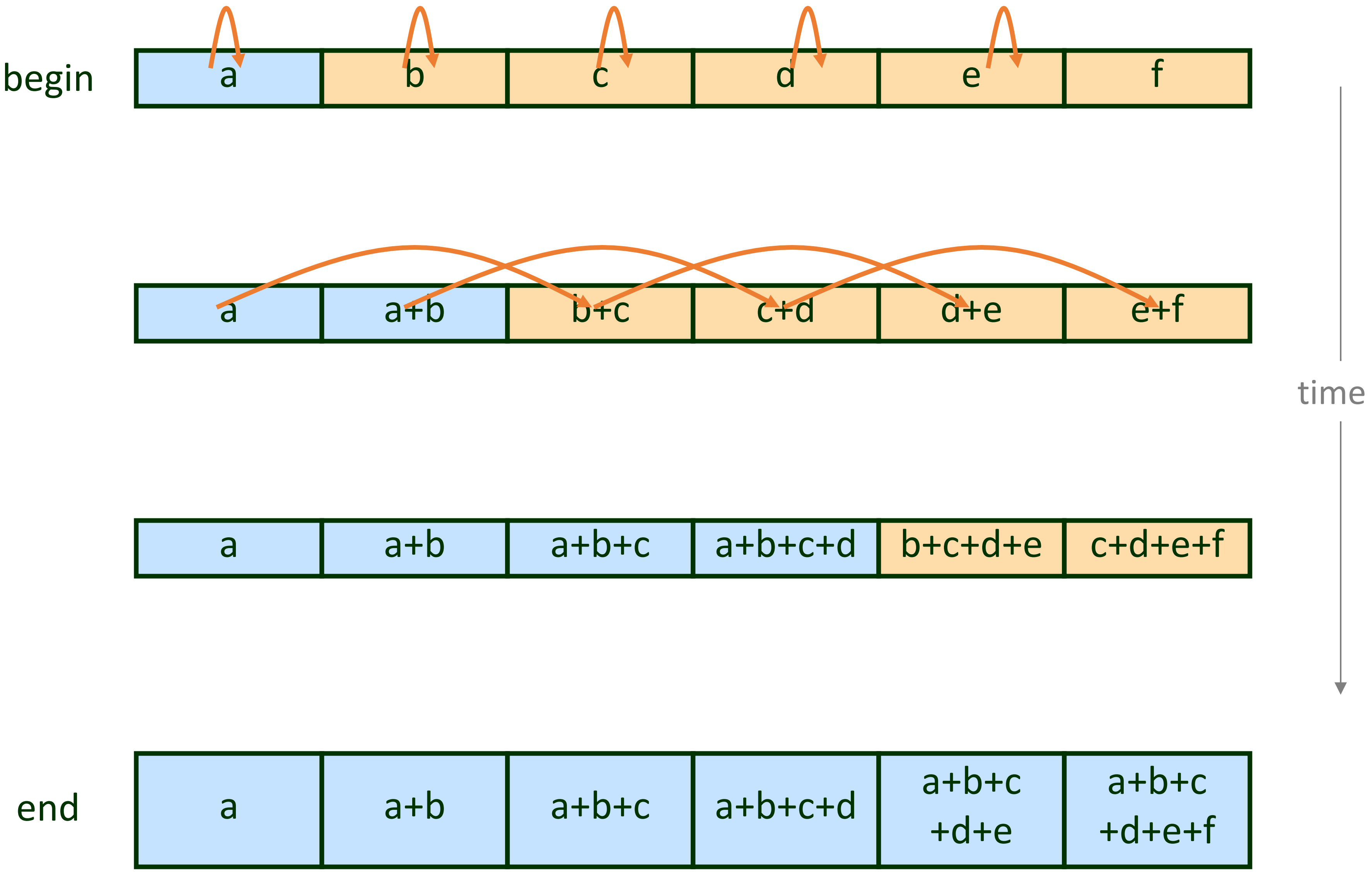

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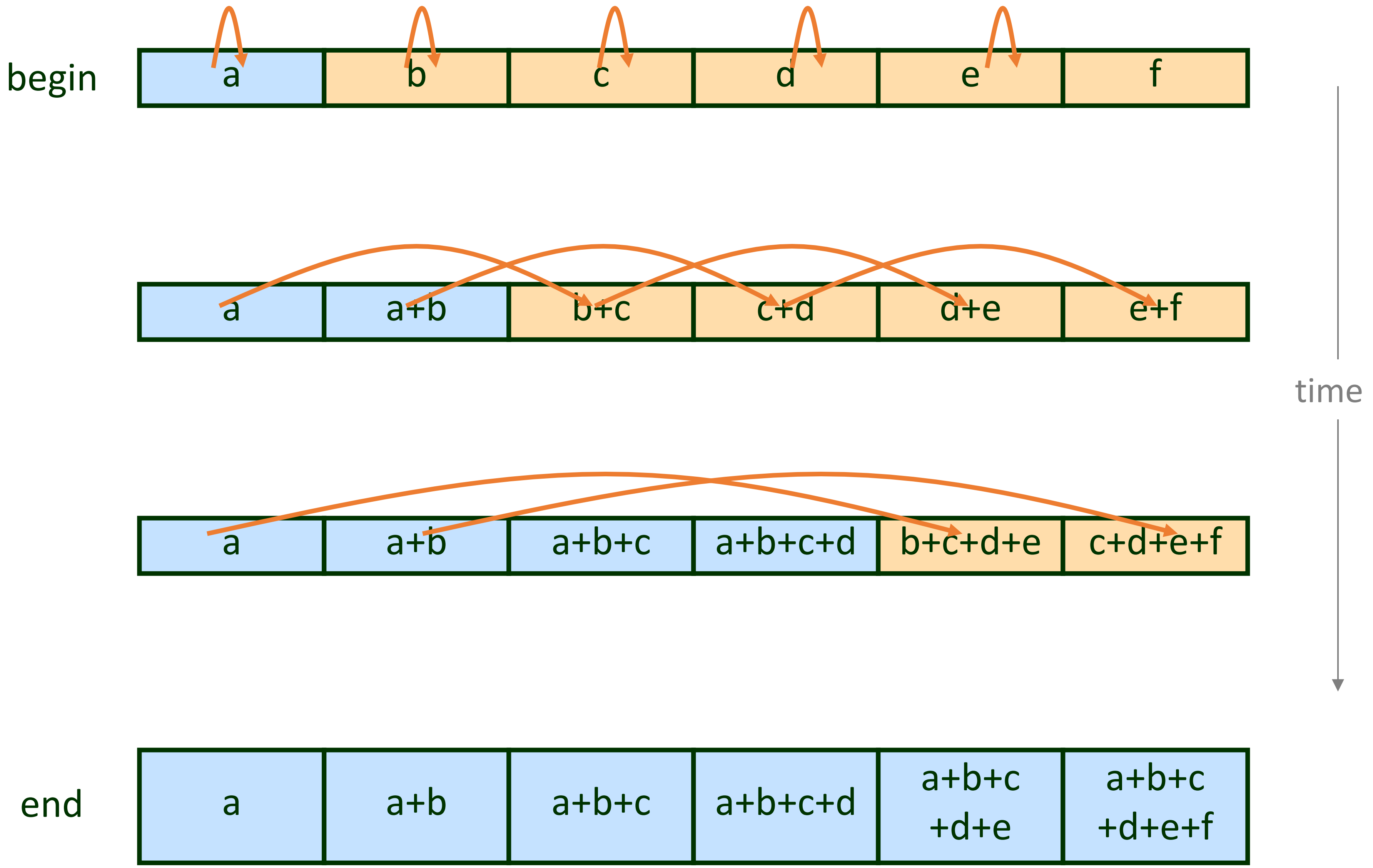
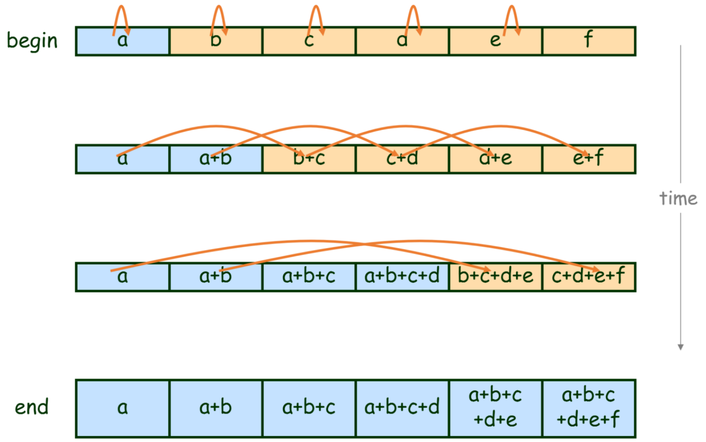


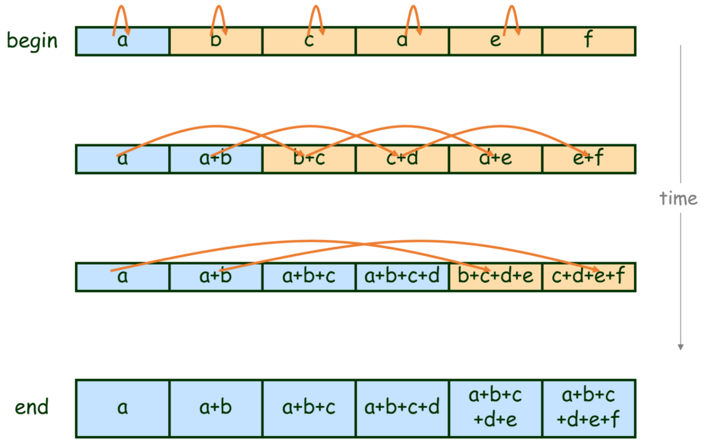
begin	a	b	c	d	e	f
	a	a+b	b+c	c+d	d+e	e+f
	a	a+b	a+b+c	a+b+c+d	b+c+d+e	c+d+e+f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Pthreads Parallel Prefix Sum



```
int g_values[N] = { a, b, c, d, e, f };

void prefix_sum_thread(void * param) {

  int i;
  int id = *((int*)param);
  int stride = 0;

  for(stride=1; stride<=N/2; stride<<1) {
    g_values[id+stride] += g_values[id];
  }

}
```

Pthreads Parallel Prefix Sum



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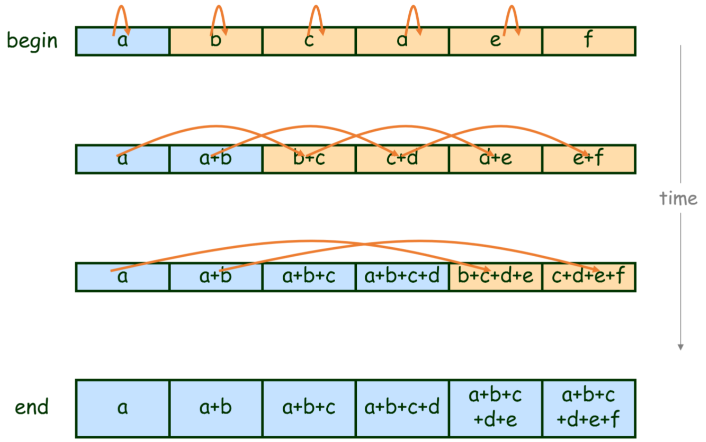
  }

}
```

Will this work?

Pthreads Parallel Prefix Sum



```
pthread_mutex_t g_locks[N] = { MUTEX_INITIALIZER, ...};
int g_values[N] = { a, b, c, d, e, f };

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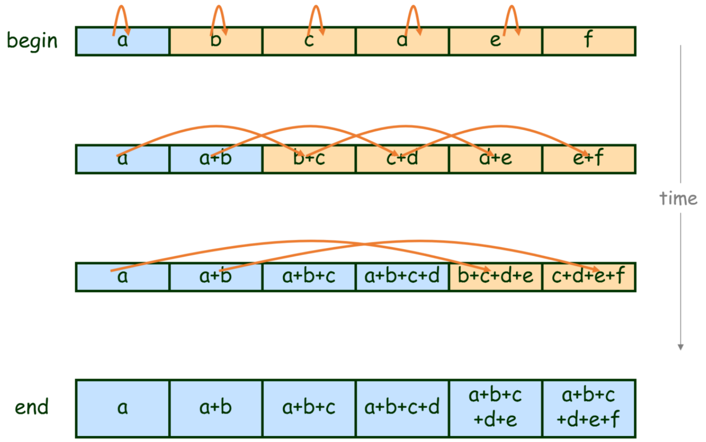
}
```



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    pthread_mutex_unlock(&g_locks[id+stride]);
  }

}
```
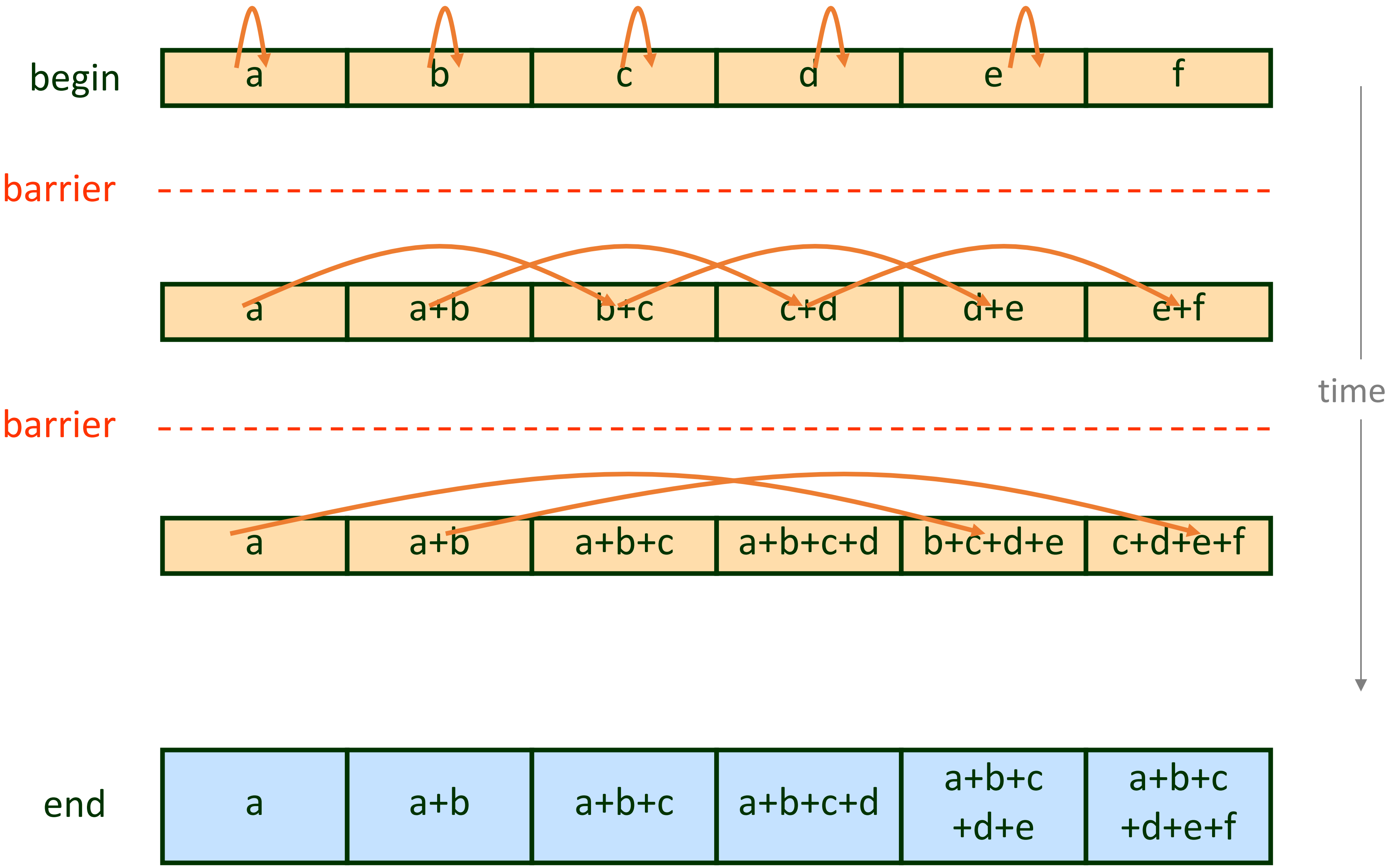

fixed?

Parallel Prefix Sum



begin	a	b	c	d	e	f
barrier						
	a	a+b	b+c	c+d	d+e	e+f
barrier						
	a	a+b	a+b+c	a+b+c+d	b+c+d+e	c+d+e+f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Barrier Basics

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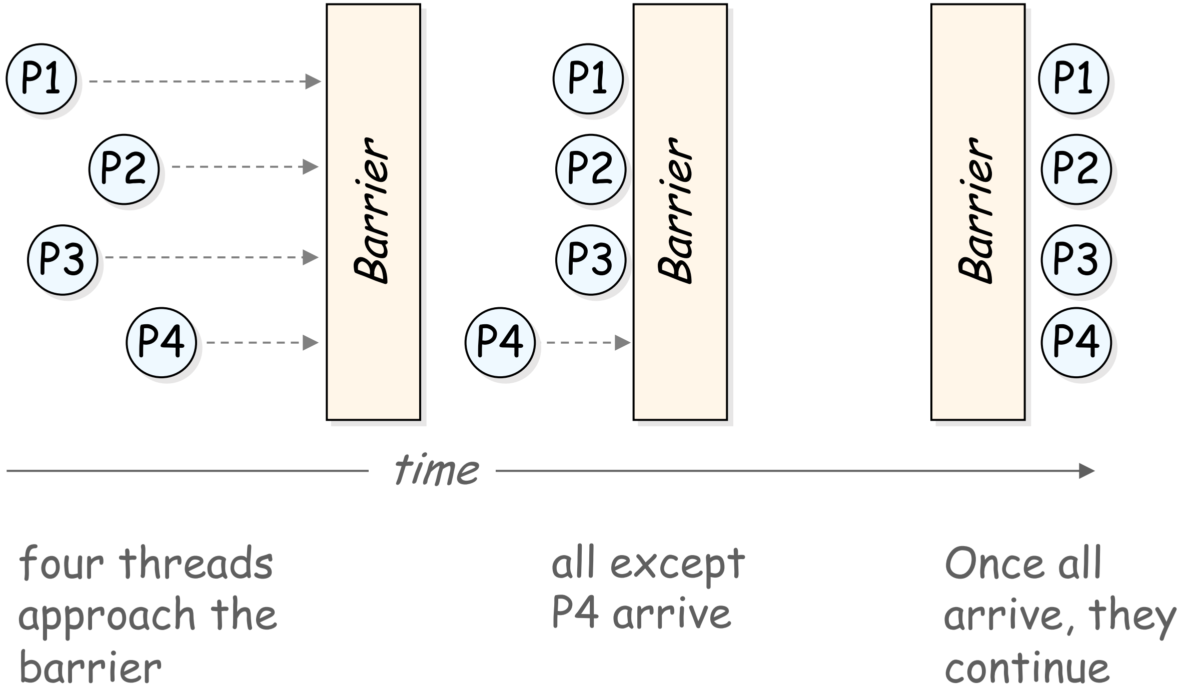

Barrier Basics

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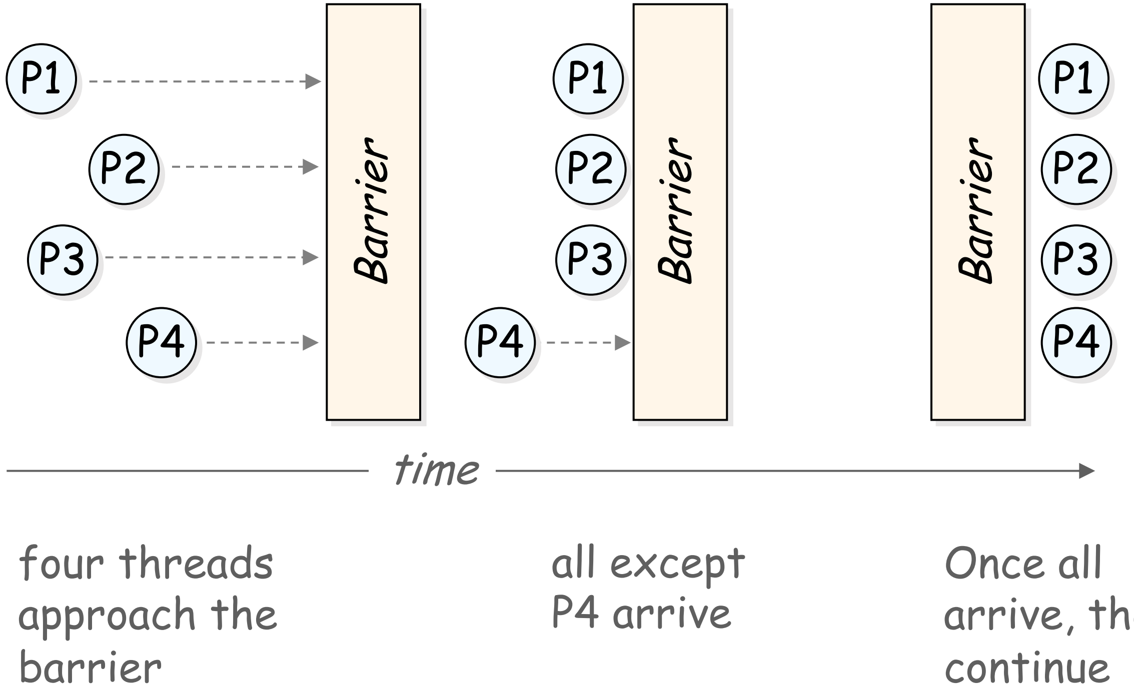
- ***Workhorse of BSP programming models***



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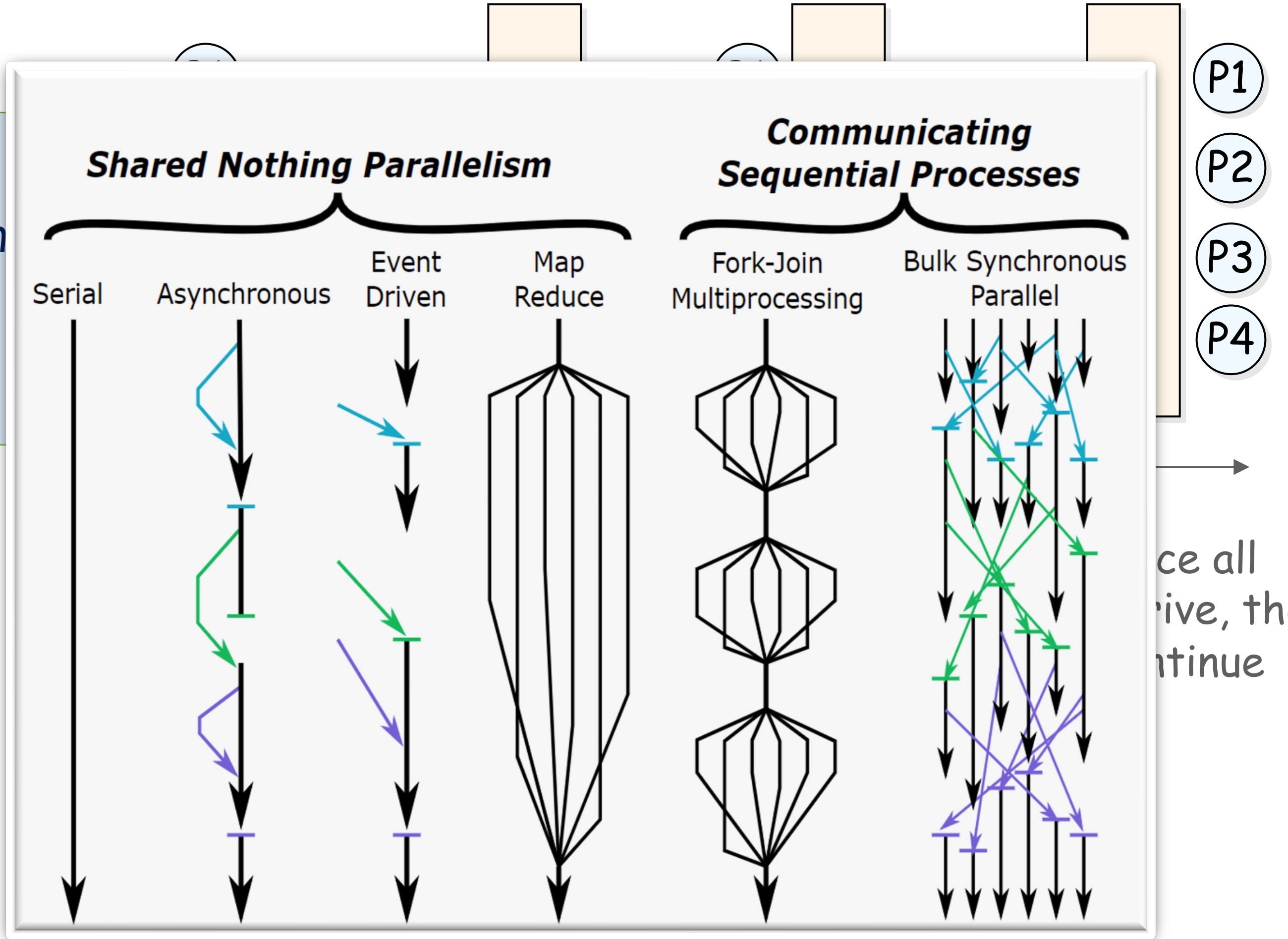

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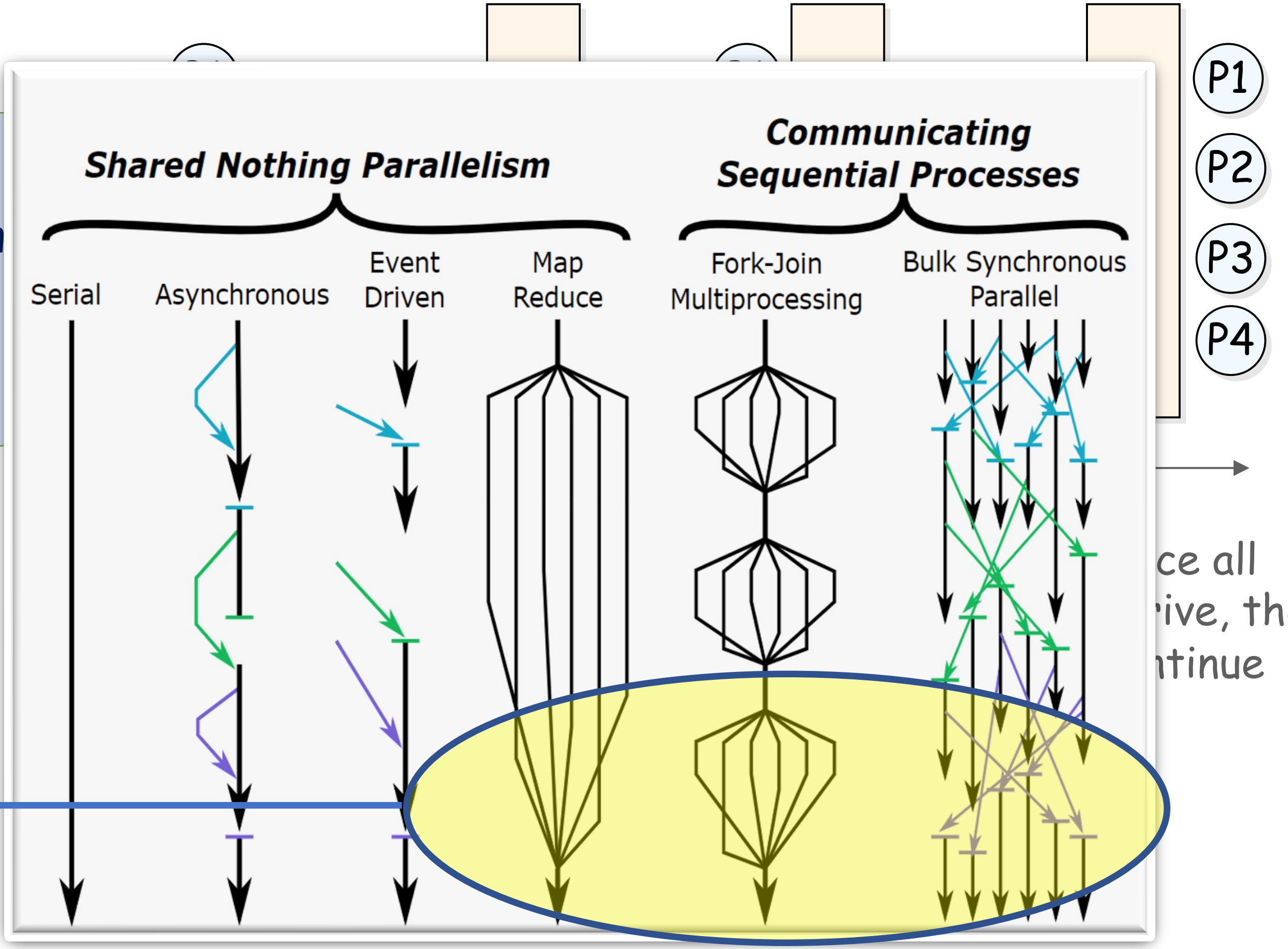

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Fundamental primitive in many parallel models

Barrier Basics

- Coordination mechanism
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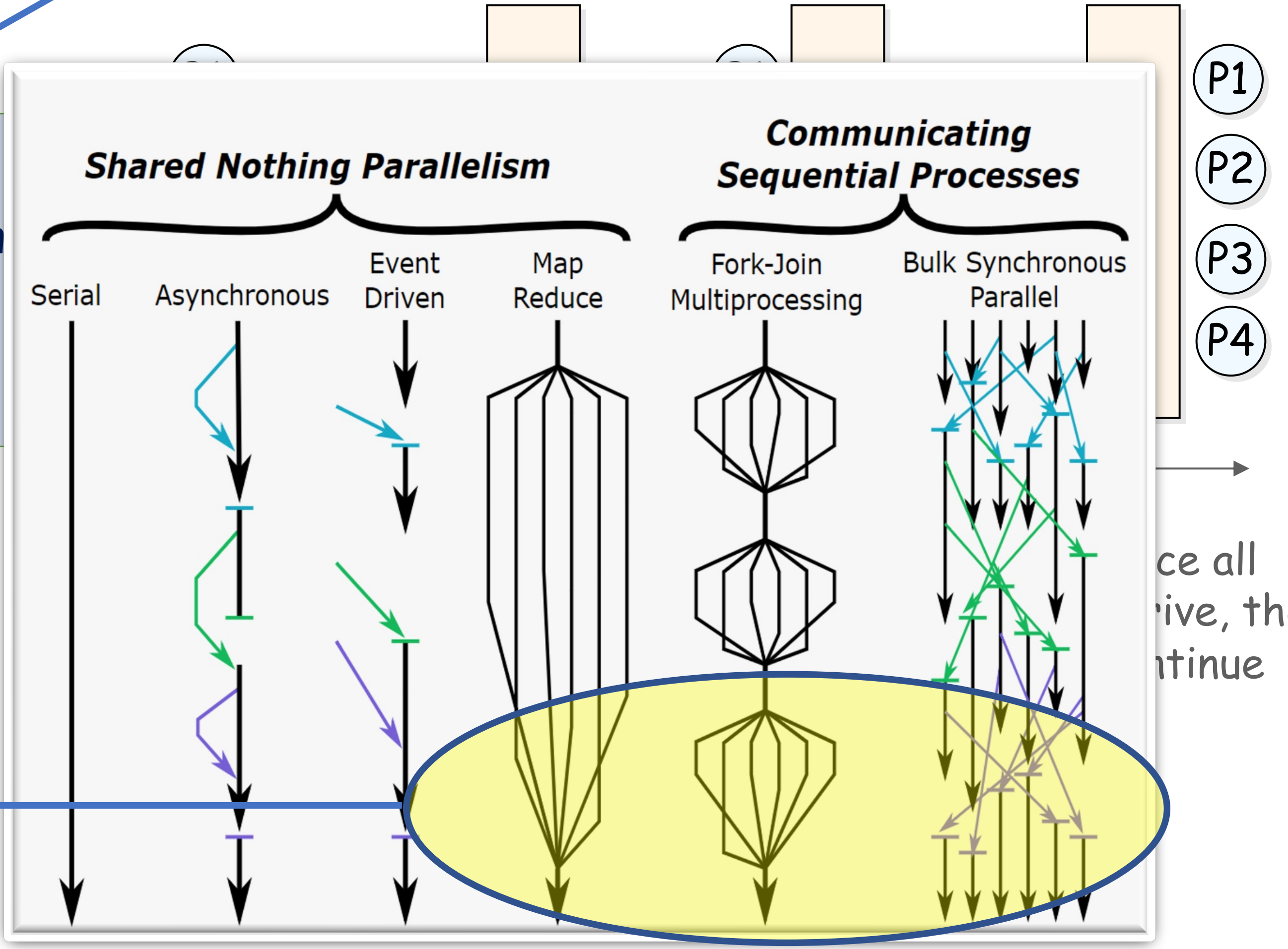
- ***Workhorse of BSP programming models***

Can you make a lock with a barrier?



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Fundamental primitive in many parallel models

Barriers: Goals

Desirable barrier properties:

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- Low contention on shared objects
- Low shared memory references per process
- No need for shared memory initialization
- Symmetric: same amount of work for all
- Algorithm simplicity
- Simple basic primitive
- Minimal propagation time
- Reusability of the barrier (must!)

Barrier Building Blocks

- Conditions
- Semaphores
- Atomic Bit
- Atomic Register
- Fetch-and-increment register
- Test and set bits
- Read-Modify-Write register

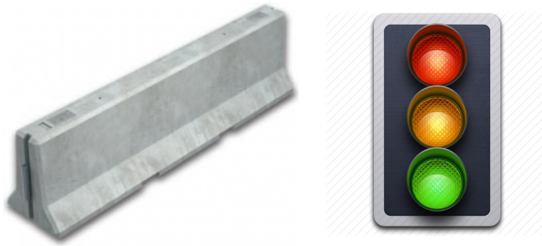
Barrier with Semaphores

Barrier using Semaphores

Algorithm for N threads

Barrier using Semaphores

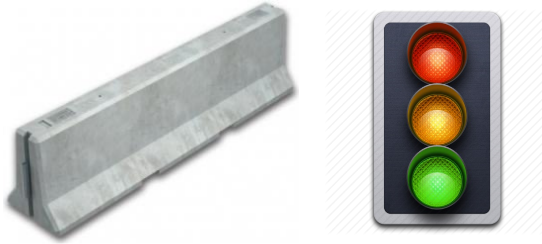
Algorithm for N threads



Barrier using Semaphores

Algorithm for N threads

```
shared    sem_t arrival = 1;          // sem_init(&arrival, NULL, 1)
          sem_t departure = 0;        // sem_init(&departure, NULL, 0)
          atomic int counter = 0;     // (gcc intrinsics are verbose)
```



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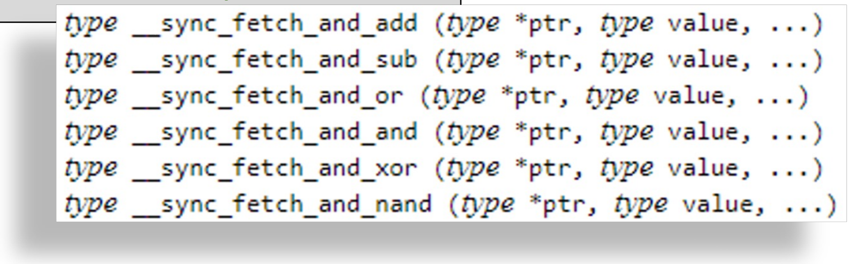
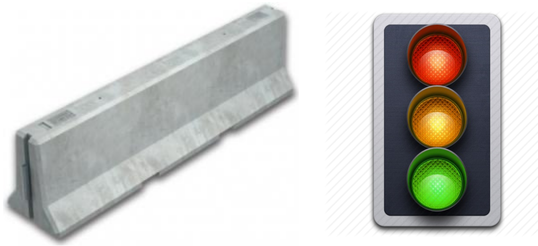


```
type __sync_fetch_and_add (type *ptr, type value, ...)
type __sync_fetch_and_sub (type *ptr, type value, ...)
type __sync_fetch_and_or (type *ptr, type value, ...)
type __sync_fetch_and_and (type *ptr, type value, ...)
type __sync_fetch_and_xor (type *ptr, type value, ...)
type __sync_fetch_and_nand (type *ptr, type value, ...)
```

Barrier using Semaphores

Algorithm for N threads



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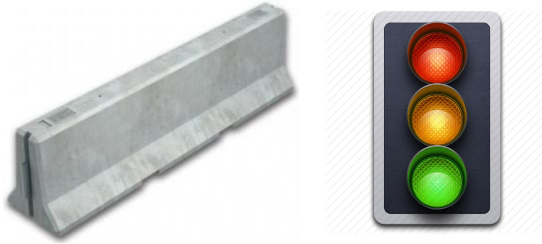

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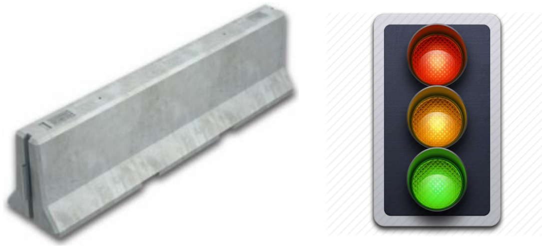
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Barrier using Semaphores

Algorithm for N threads



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Phase I

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Barrier using Semaphores

Algorithm for N threads

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else
  sem_post(arrival)
```
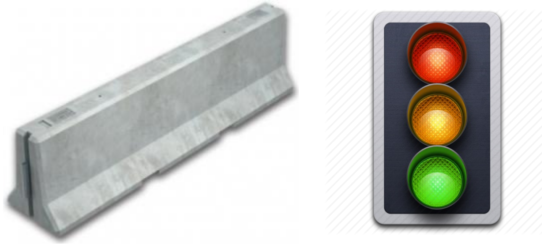

First N-1 threads post on arrival, wait on departure

Barrier using Semaphores

Algorithm for N threads



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shared      sem_t arrival = 1;            // sem_init(&arrival, NULL, 1)
            sem_t departure = 0;          // sem_init(&departure, NULL, 0)
            atomic int counter = 0;       // (gcc intrinsics are verbose)
```

Phase I

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

First N-1 threads post on arrival, wait on departure

Nth thread post on departure, releasing threads into phase II (what is value of arrival?)

Barrier using Semaphores

Algorithm for N threads

```
shared    sem_t arrival = 1;           // sem_init(&arrival, NULL, 1)
          sem_t departure = 0;         // sem_init(&departure, NULL, 0)
          atomic int counter = 0;      // (gcc intrinsics are verbose)
```

Phase I

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

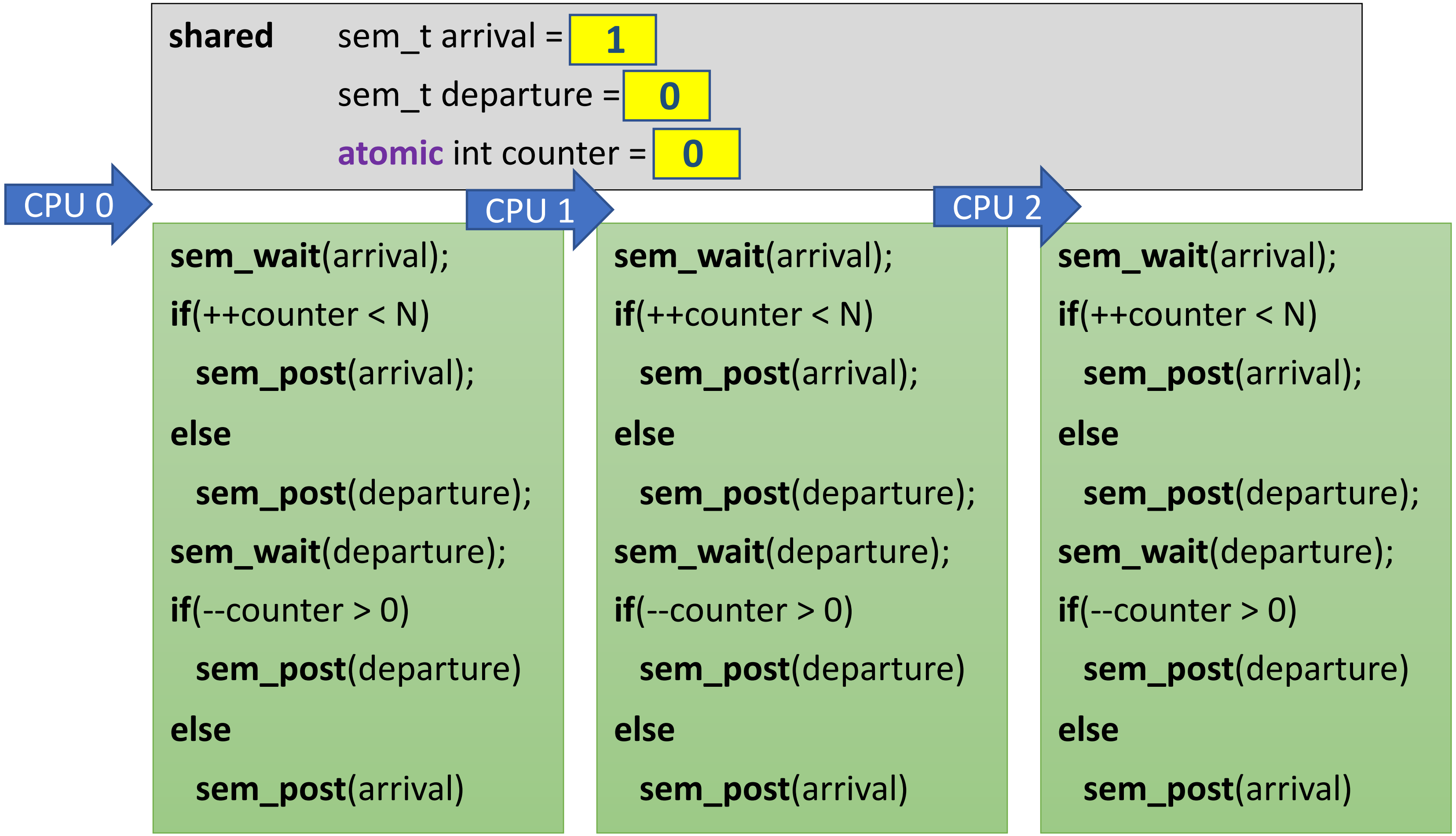
First N-1 threads post on arrival, wait on departure

Nth thread post on departure, releasing threads into phase II (what is value of arrival?)

First N-1 threads post on departure, last posts arrival

Semaphore Barrier Action Zone

N == 3



shared sem_t arrival = **1**

sem_t departure = **0**

atomic int counter = **0**

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

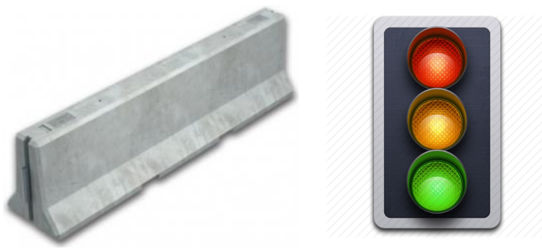
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

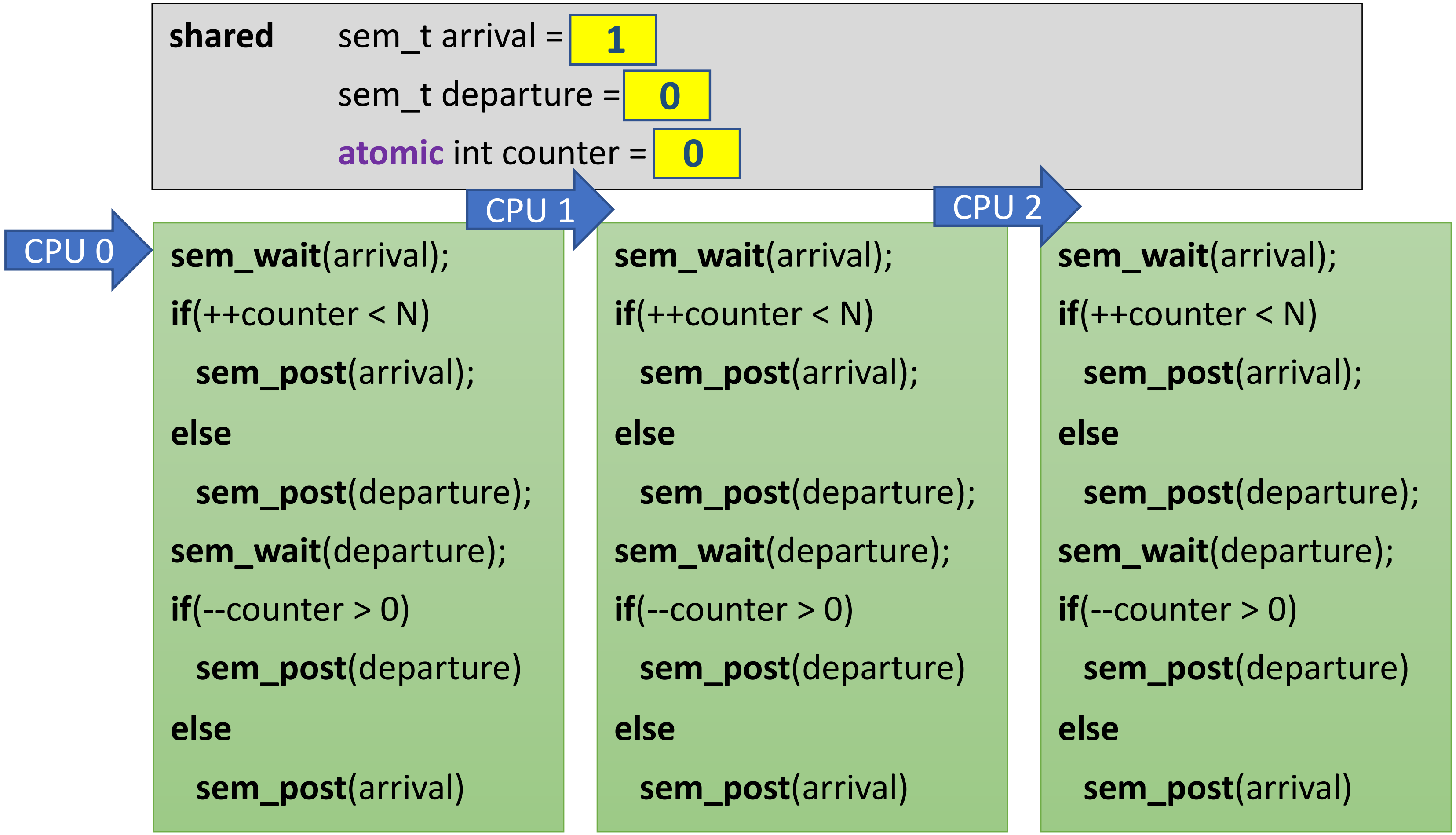
CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





shared sem_t arrival = **1**

sem_t departure = **0**

atomic int counter = **0**

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

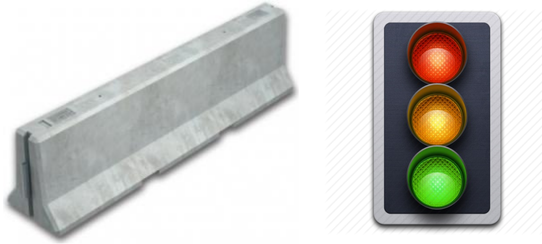
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

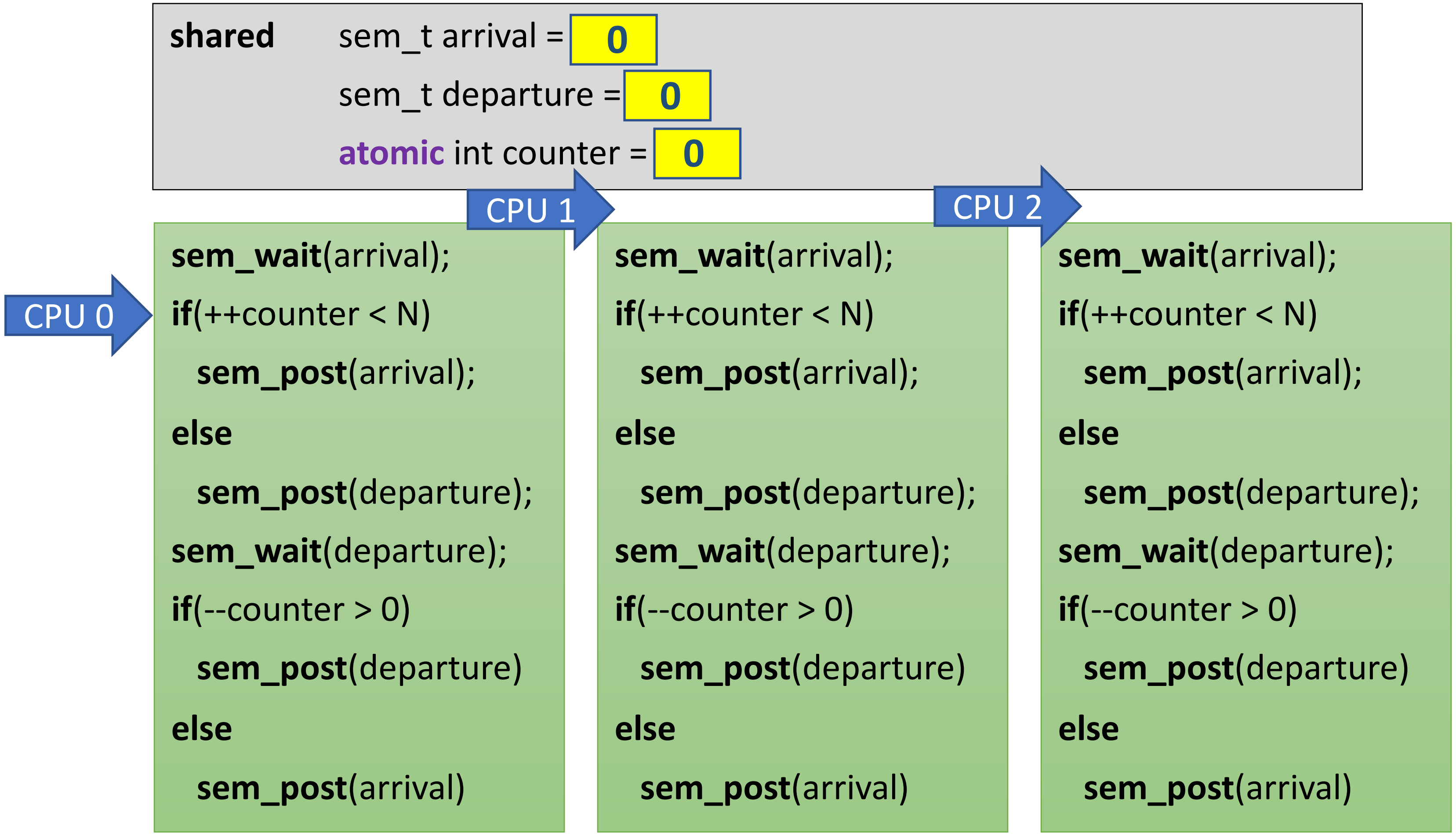
CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 0
```

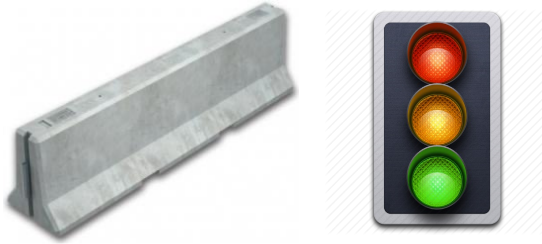
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

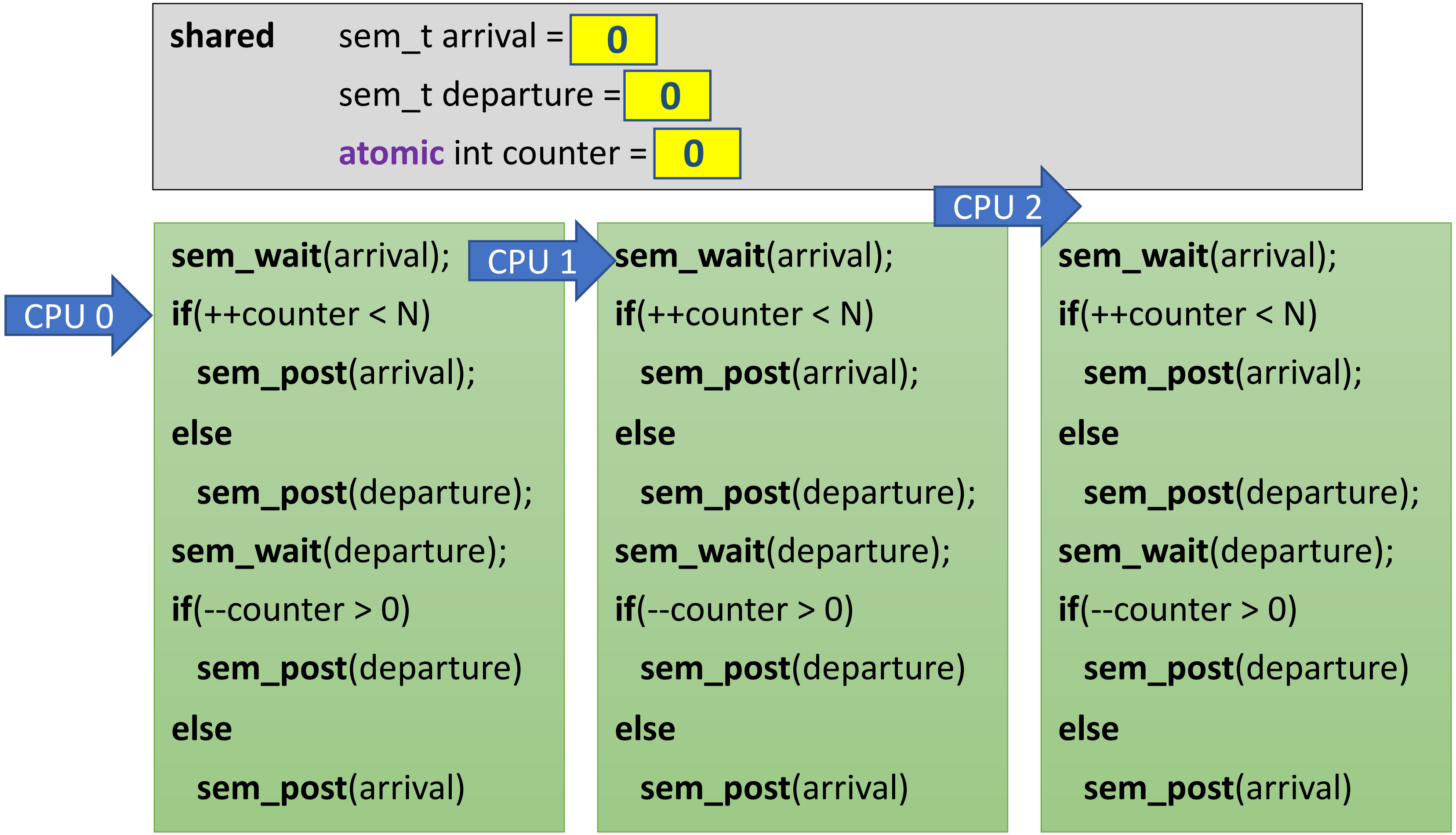
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





shared sem_t arrival = 0

sem_t departure = 0

atomic int counter = 0

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

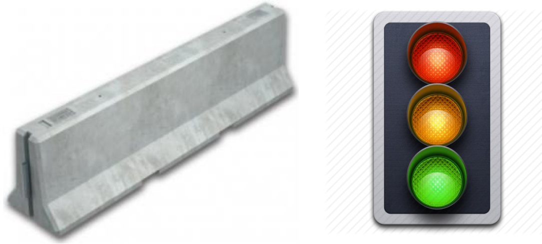
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

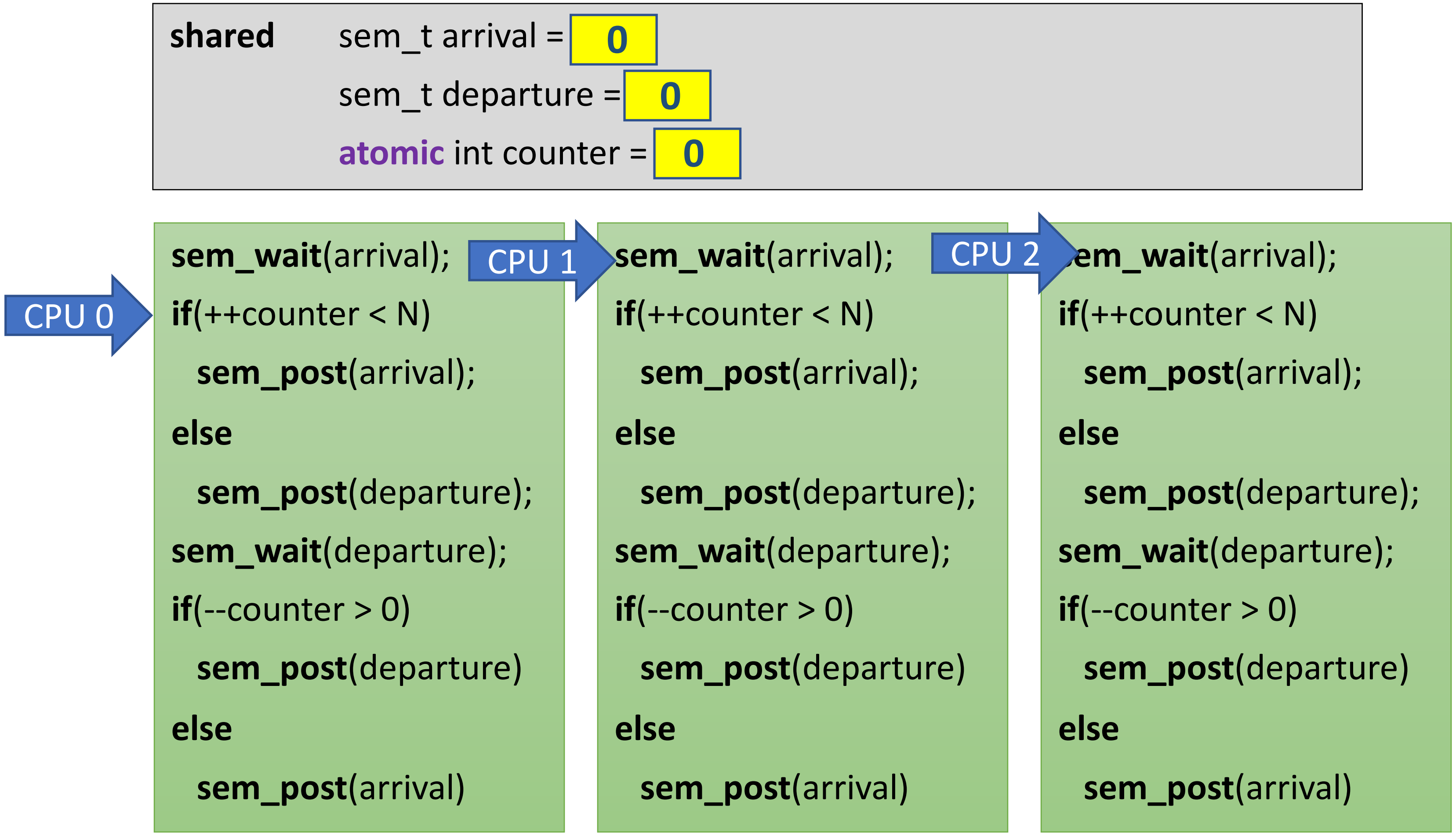
CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





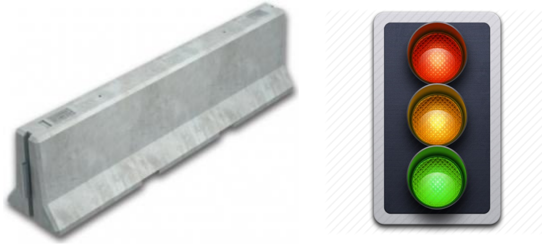
shared

```
sem_t arrival = 0
sem_t departure = 0
atomic int counter = 0
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

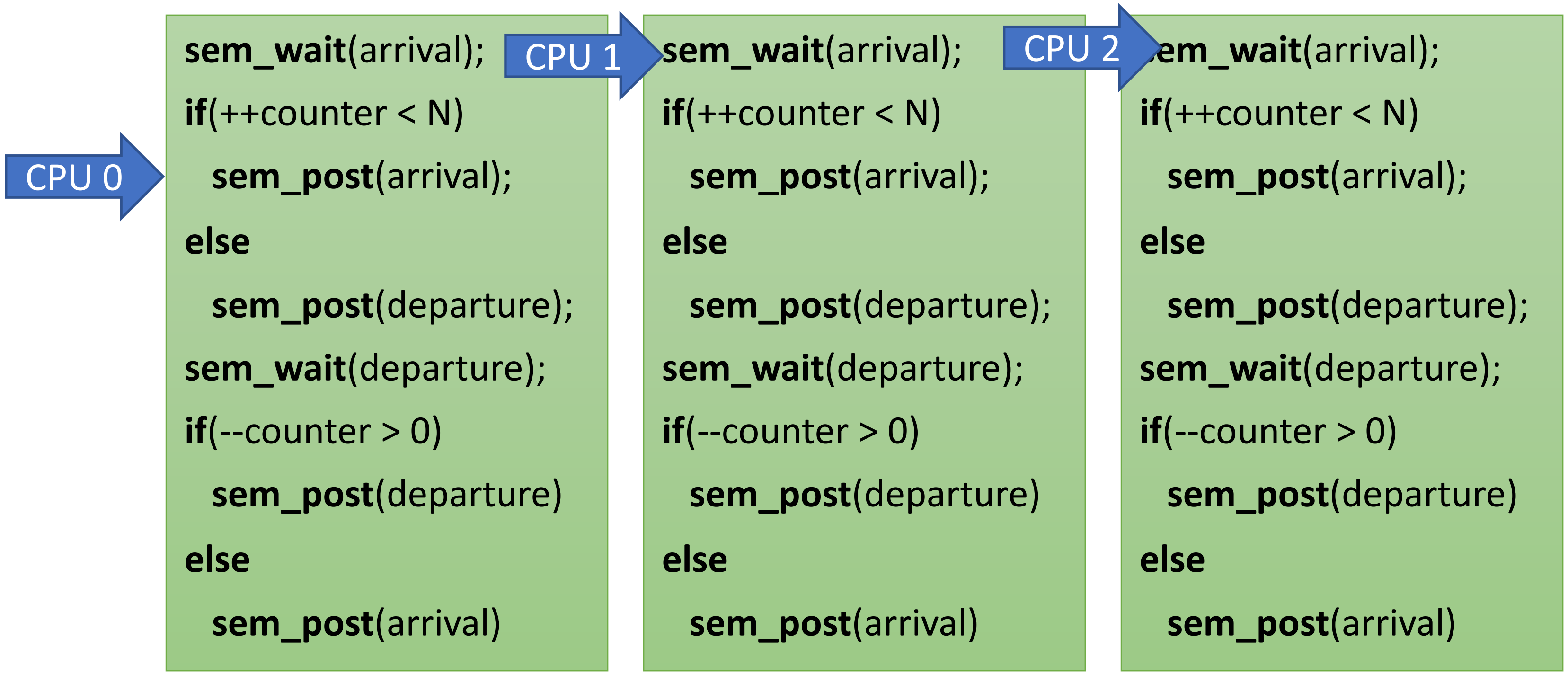
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```



Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 1
```



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

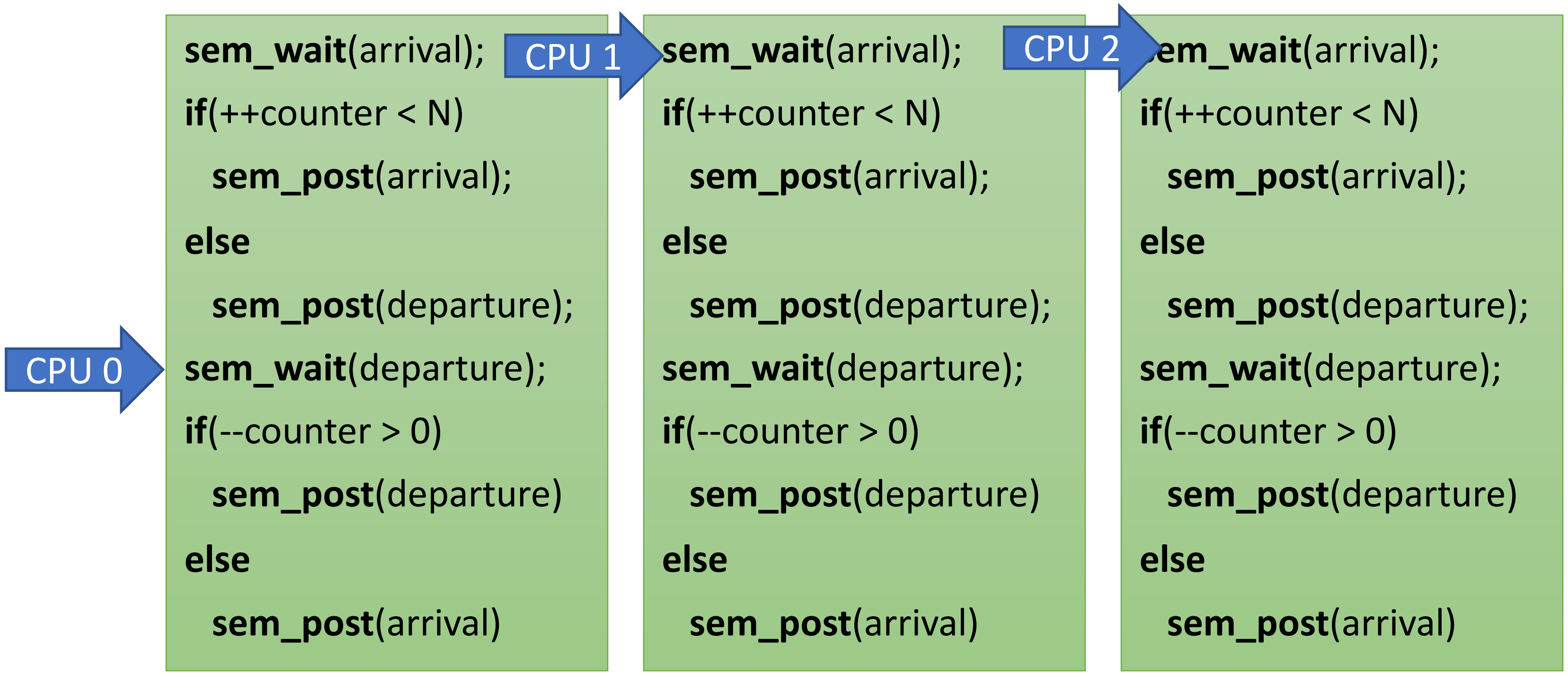
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

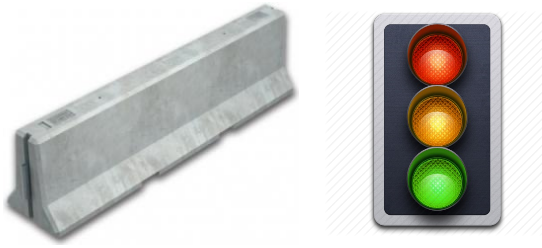
```
shared    sem_t arrival = 1
          sem_t departure = 0
          atomic int counter = 1
```



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

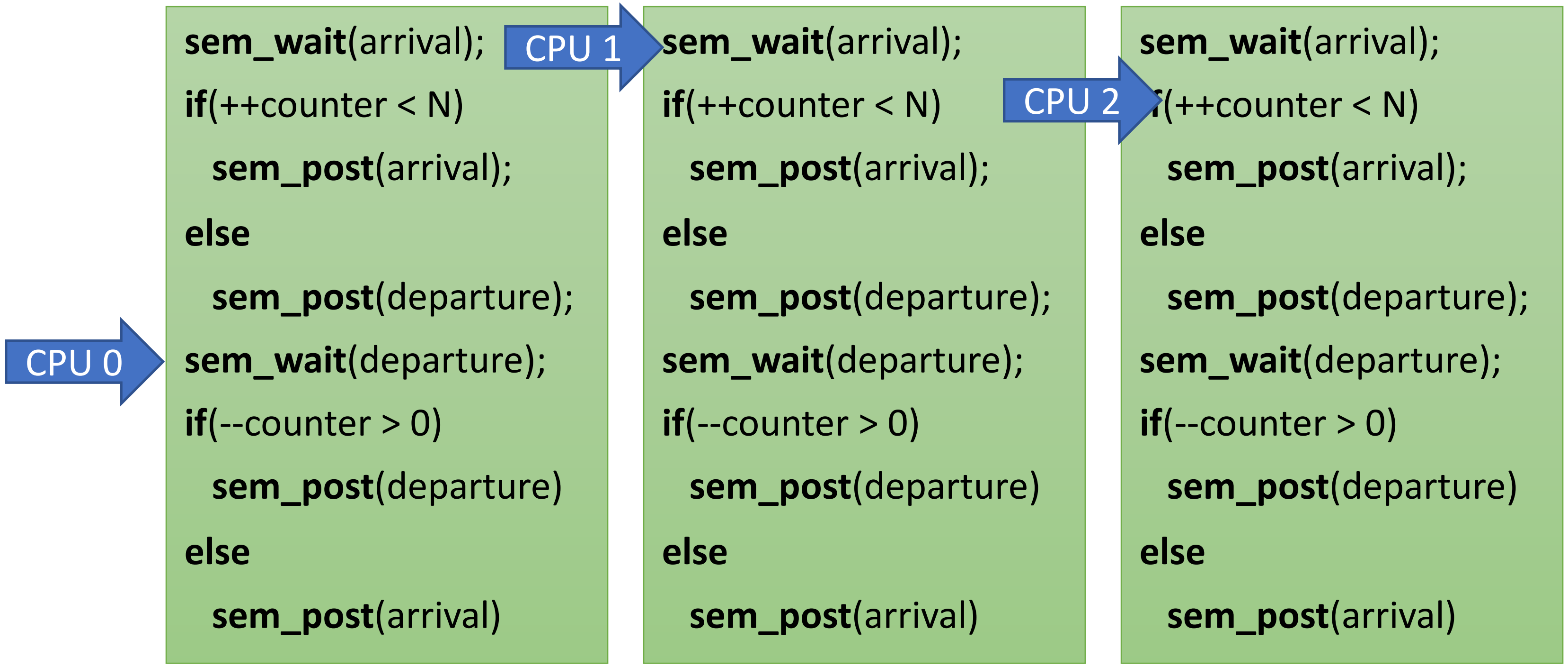
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```



Semaphore Barrier Action Zone

N == 3

```
shared     sem_t arrival = 0
           sem_t departure = 0
           atomic int counter = 1
```



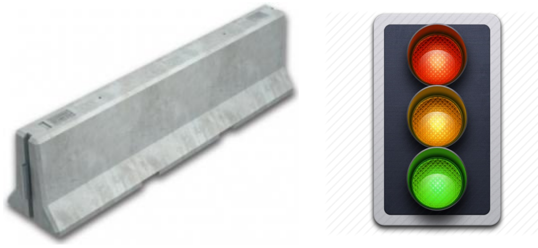
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

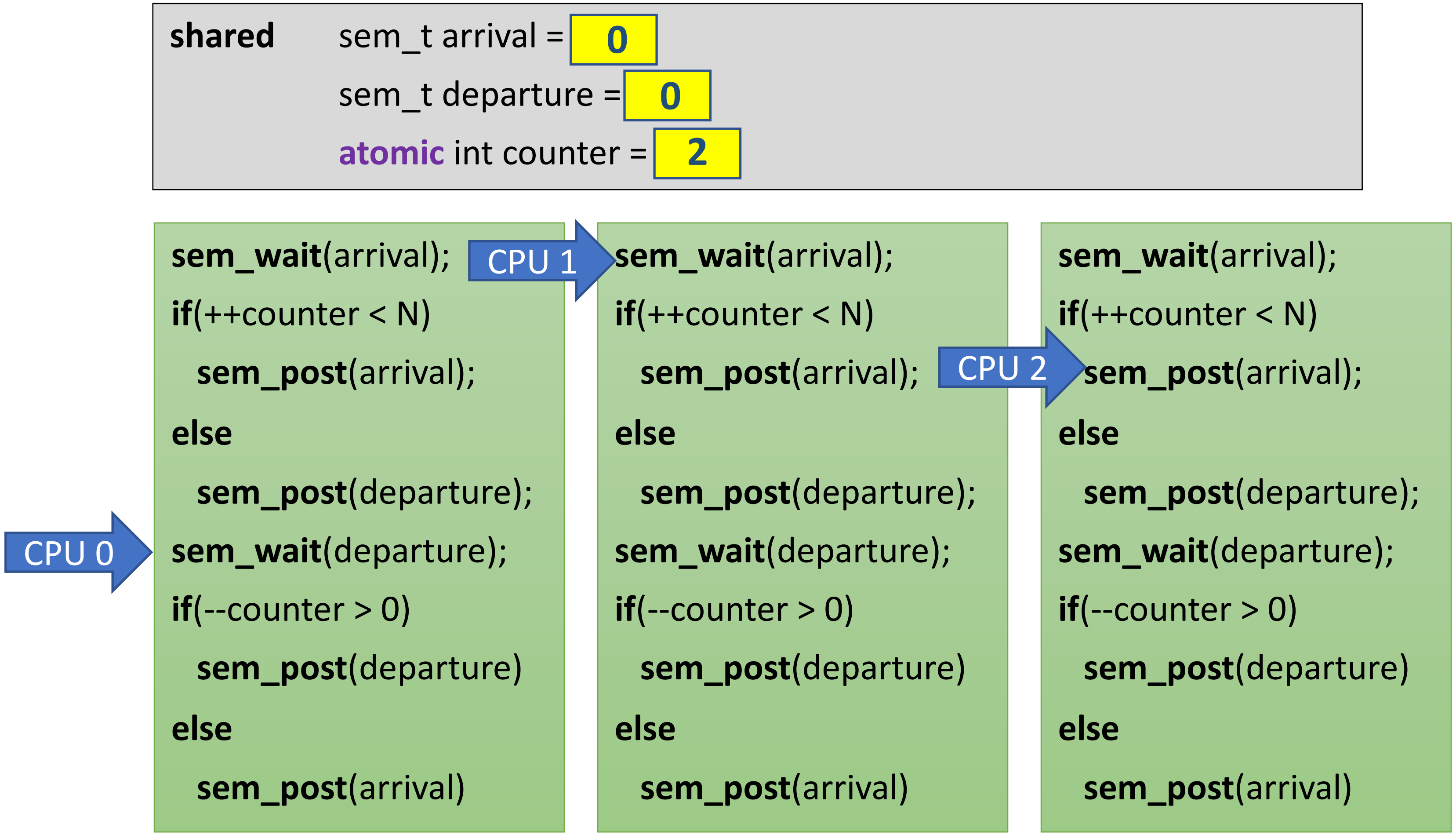
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





shared sem_t arrival = **0**

sem_t departure = **0**

atomic int counter = **2**

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = **1**
sem_t departure = **0**
atomic int counter = **2**

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

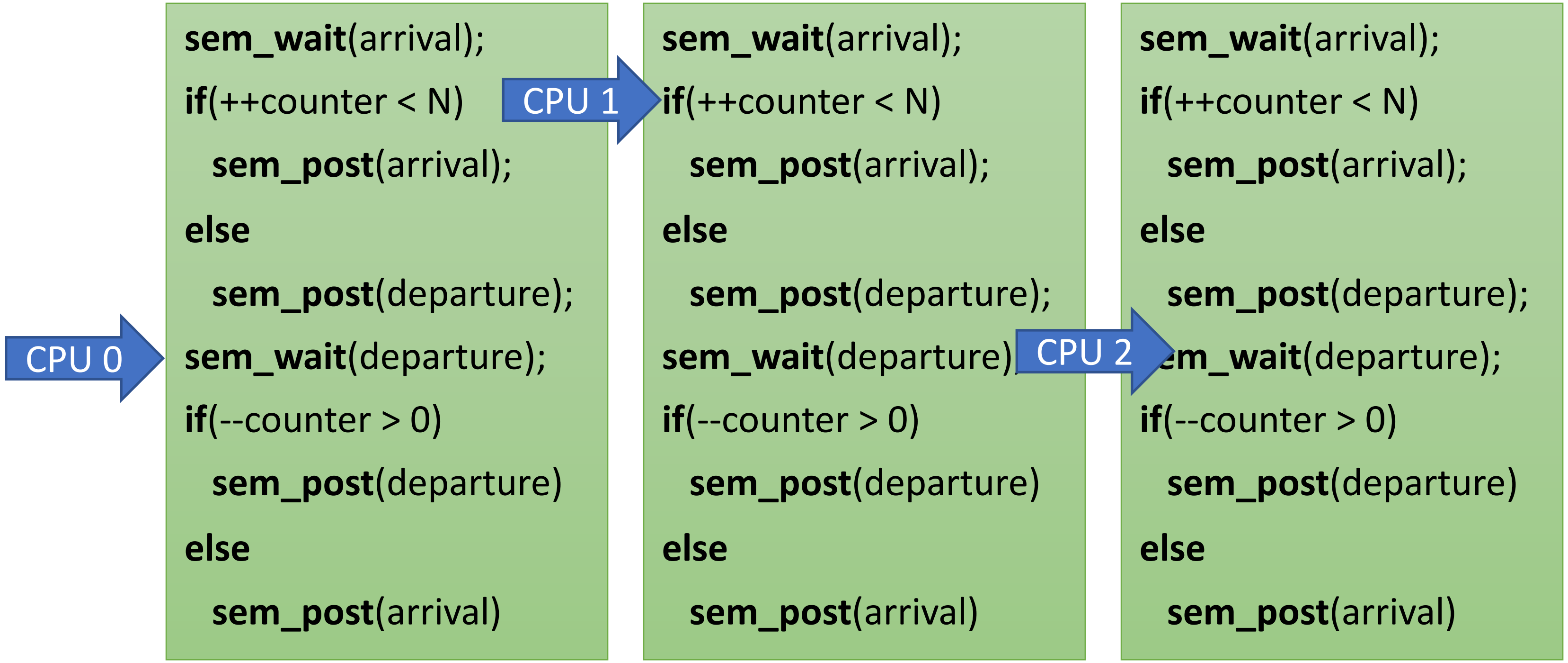
Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = **0**

sem_t departure = **0**

atomic int counter = **2**



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

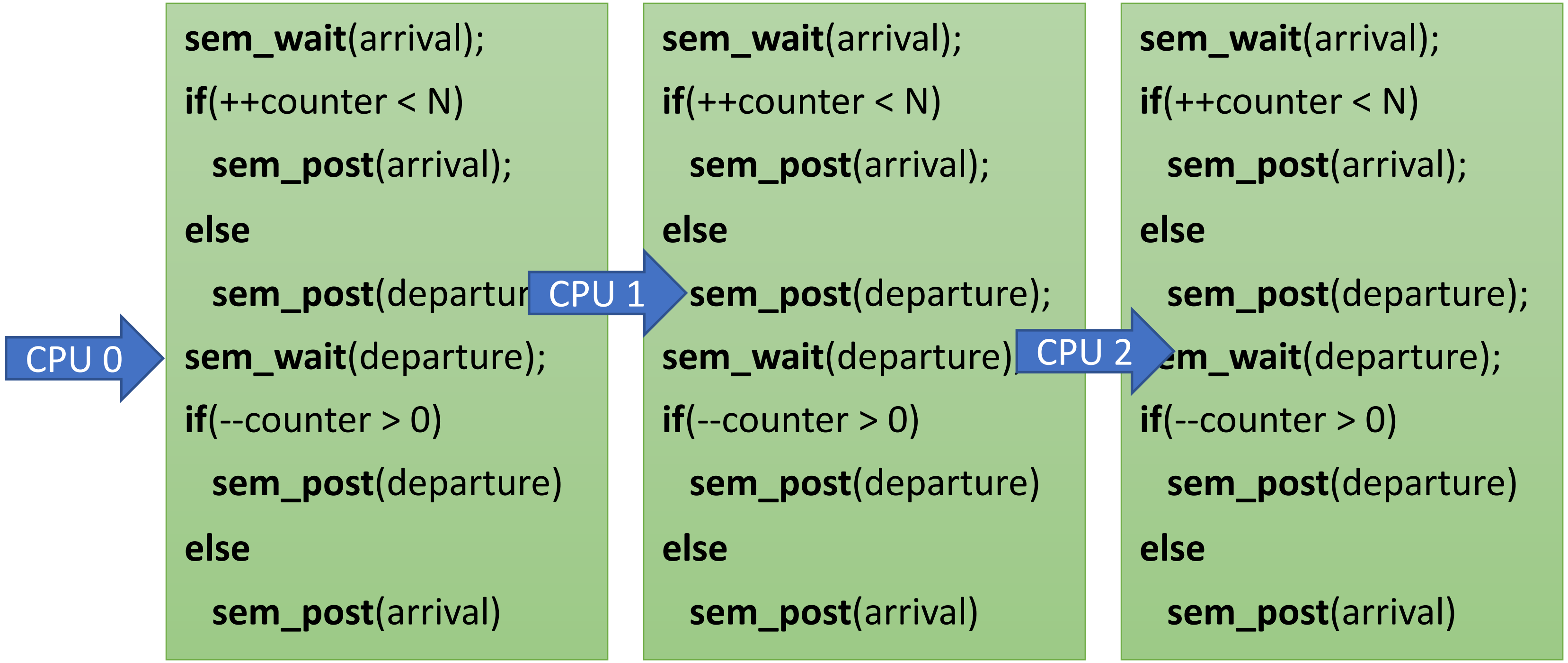
Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = 0

sem_t departure = 0

atomic int counter = 3



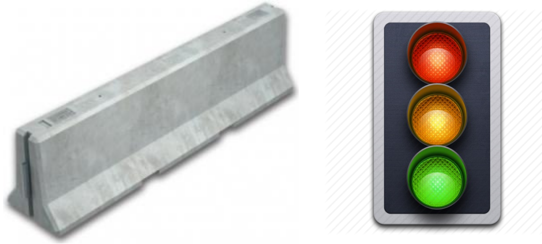
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departur
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

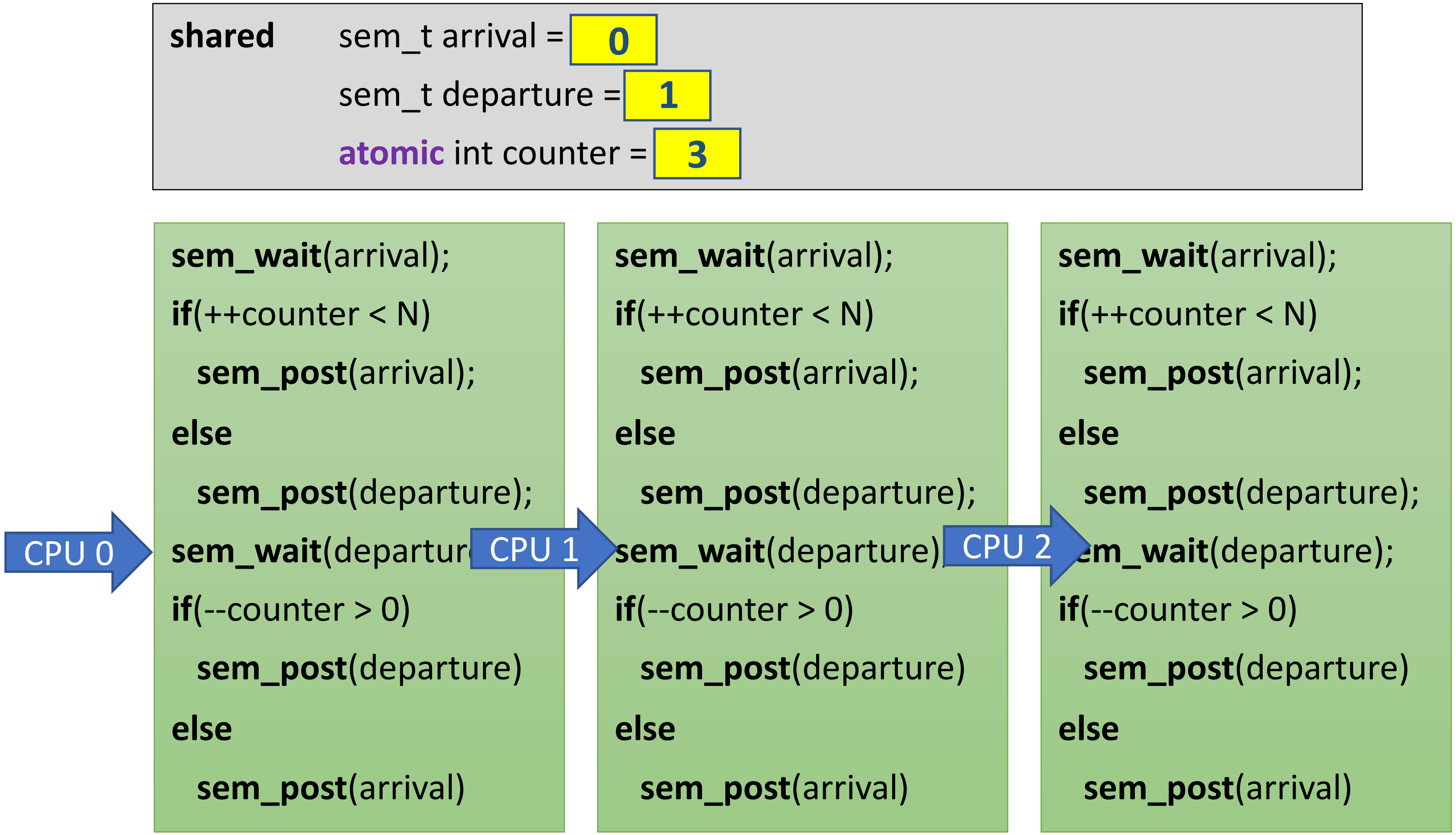
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure)
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
em_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





shared sem_t arrival = **0**

sem_t departure = **1**

atomic int counter = **3**

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departur
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

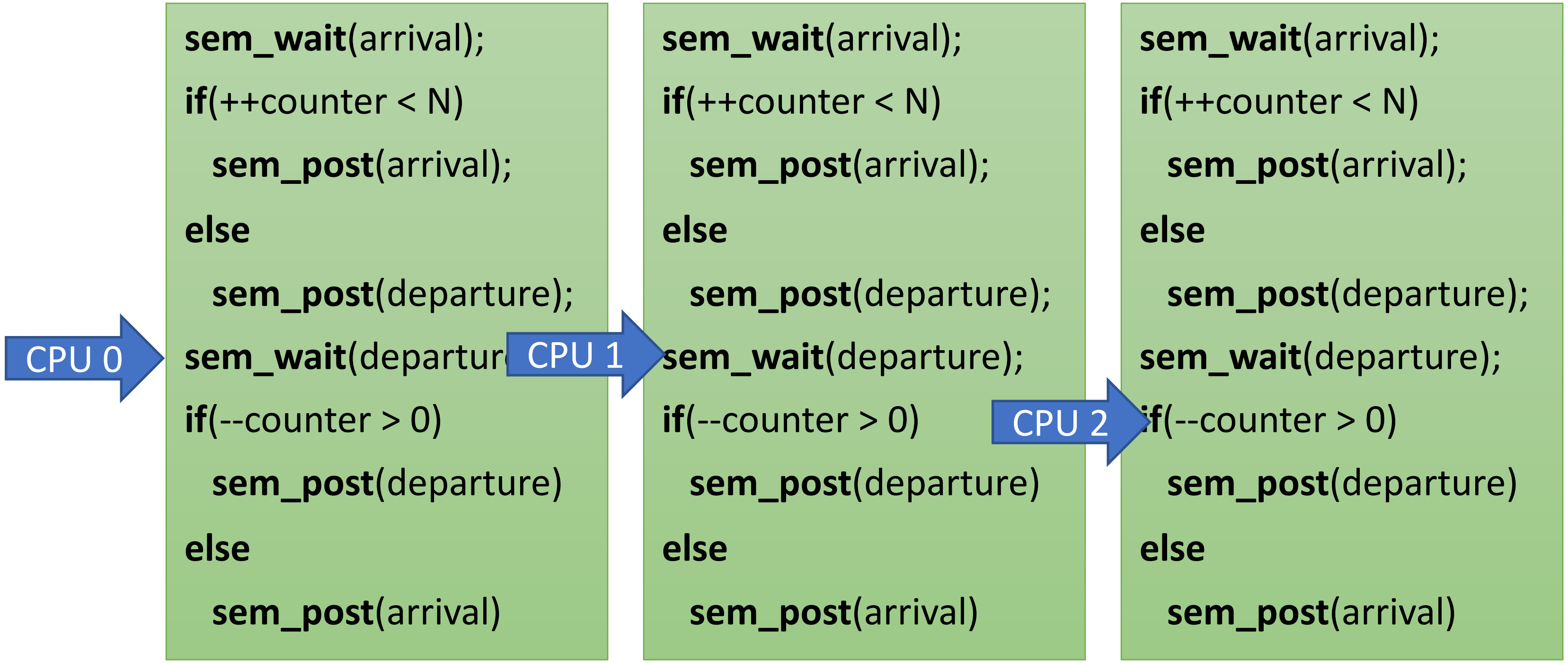
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure)
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
em_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 3
```



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

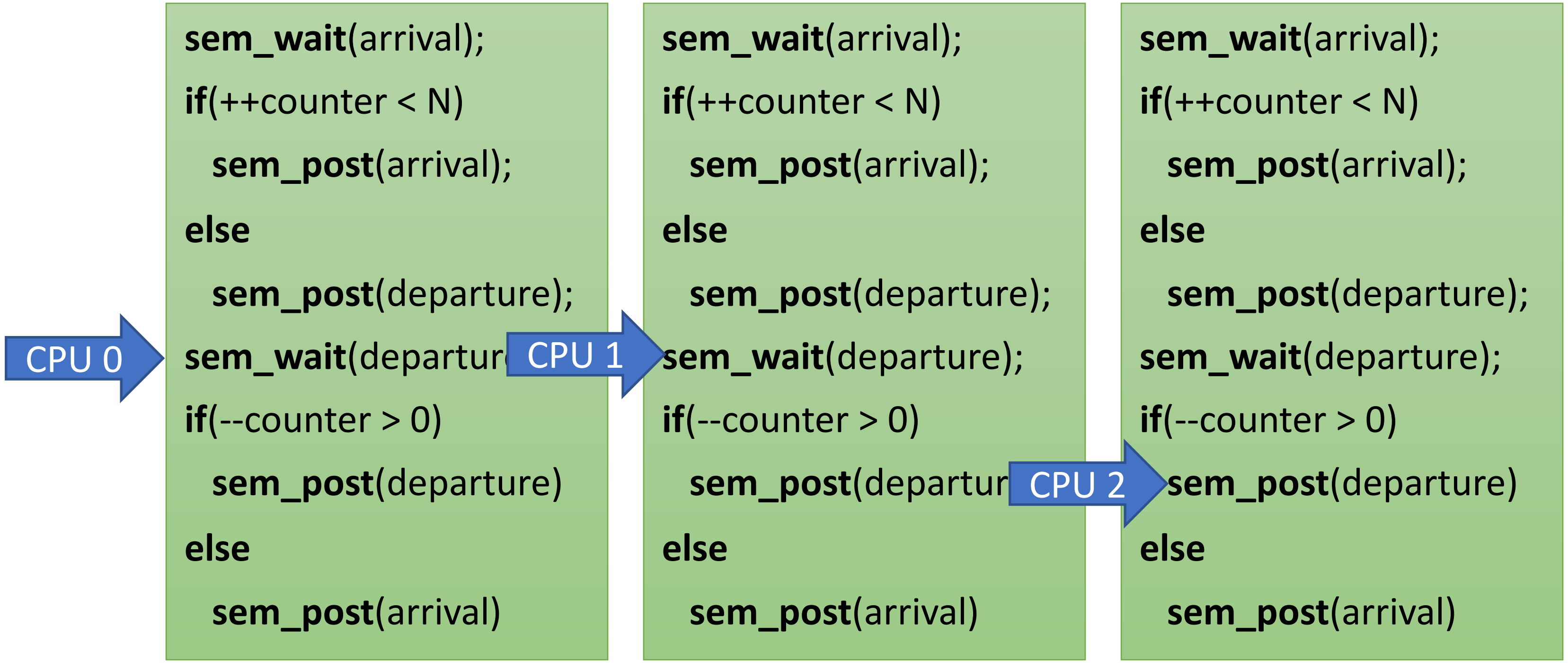
Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = **0**

sem_t departure = **0**

atomic int counter = **2**



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

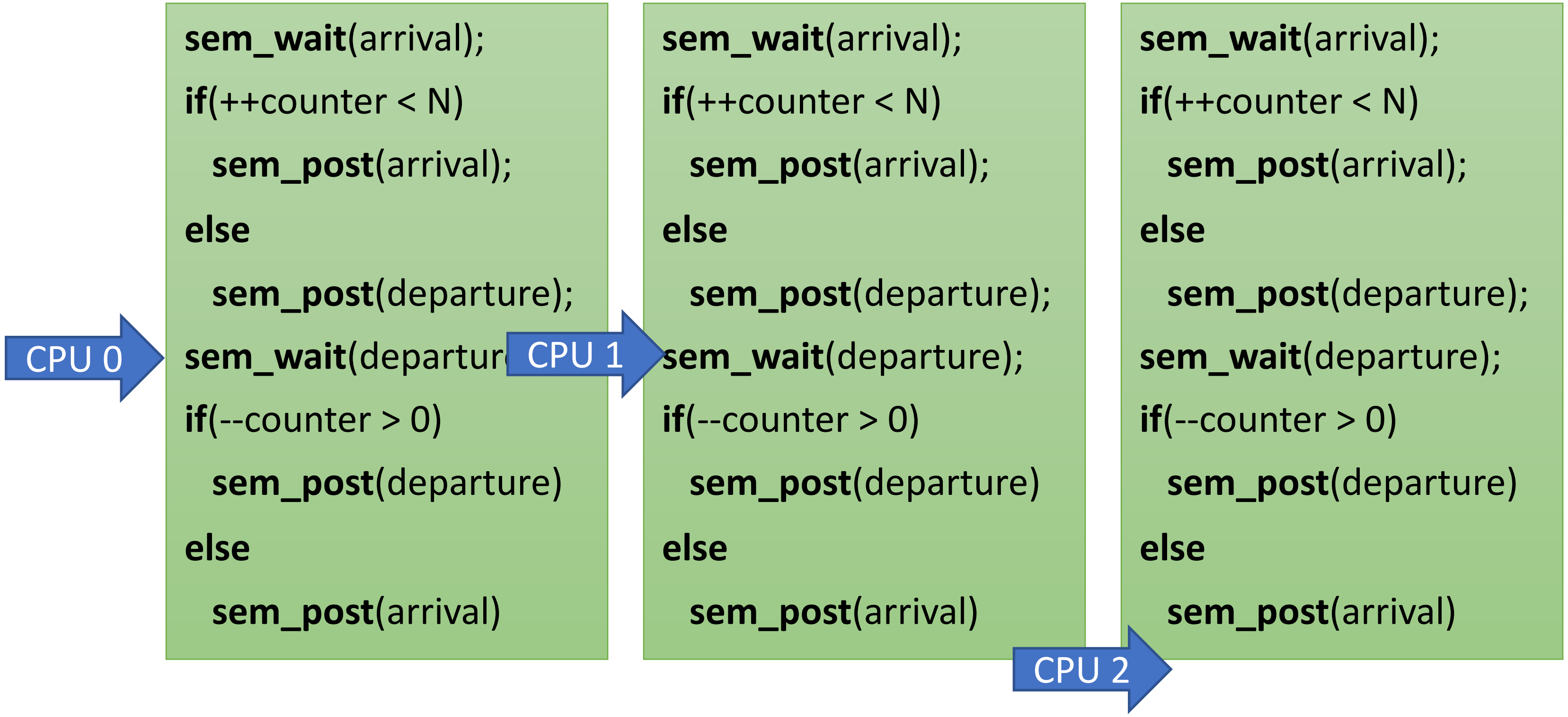
Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = 0

sem_t departure = 1

atomic int counter = 2



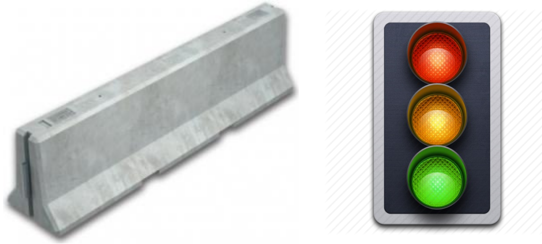
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

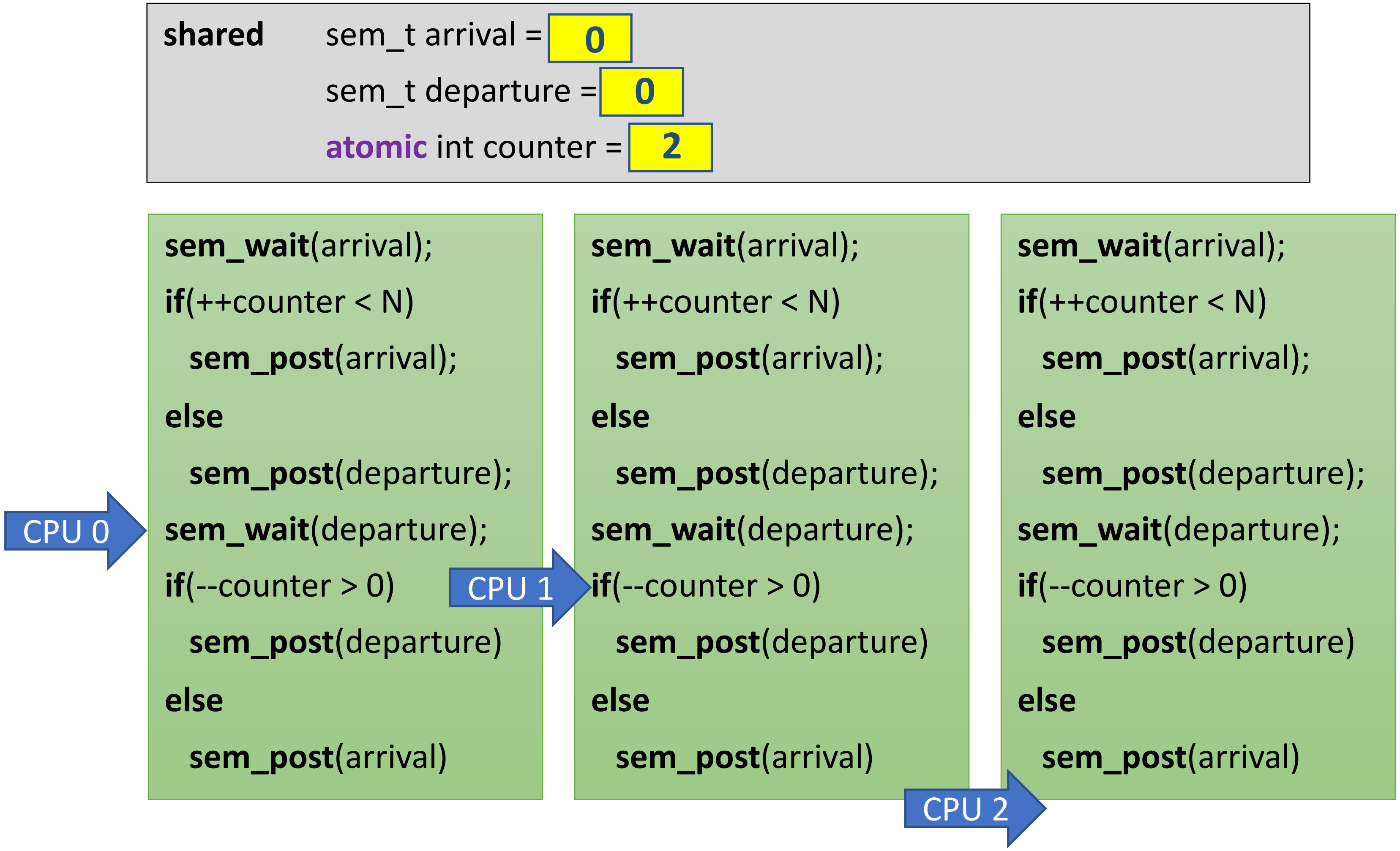
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3





shared sem_t arrival = **0**
sem_t departure = **0**
atomic int counter = **2**

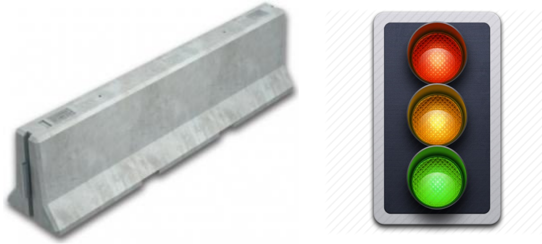
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

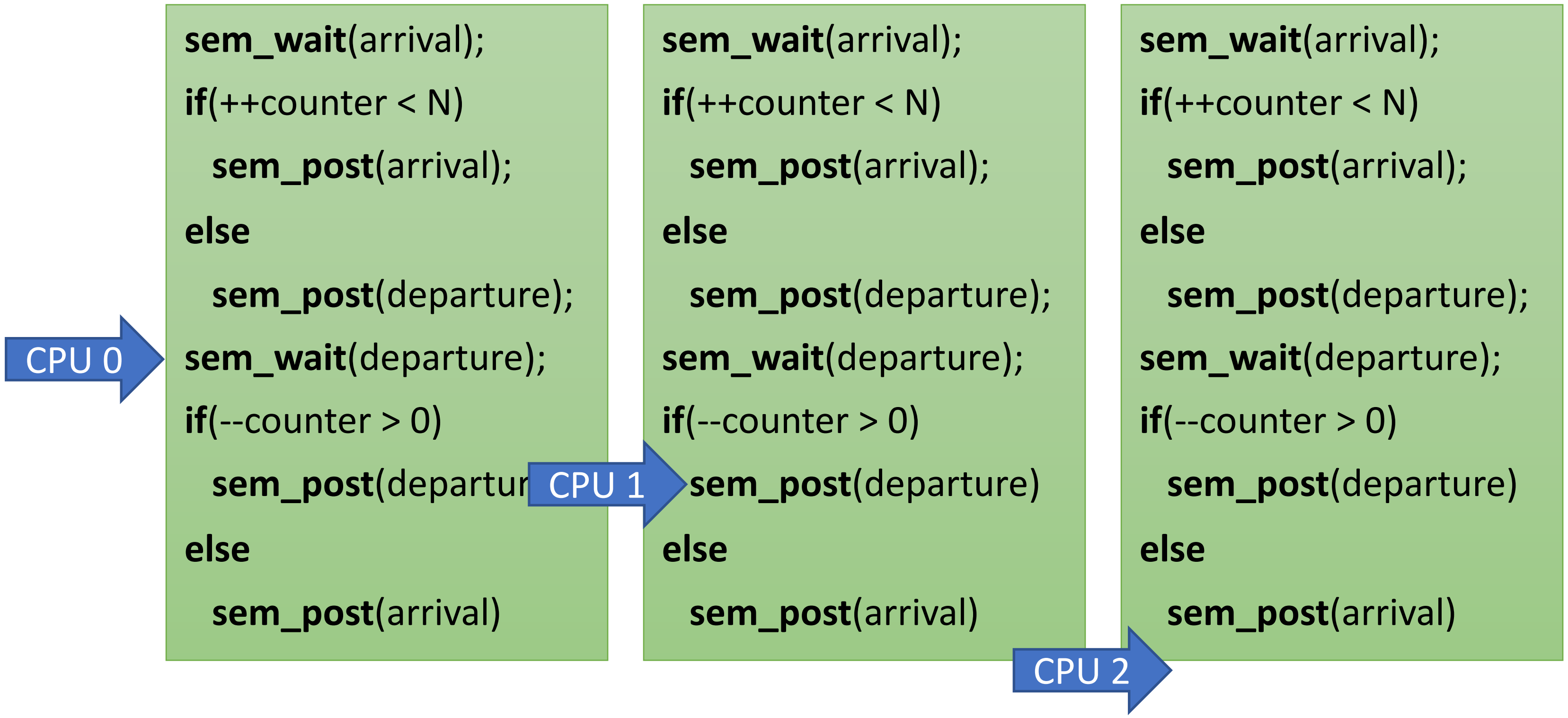
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared      sem_t arrival = 0
            sem_t departure = 0
            atomic int counter = 1
```



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departur
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

shared
sem_t arrival = **0**
sem_t departure = **1**
atomic int counter = **1**

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 0 → sem_wait(departure);

CPU 1 →

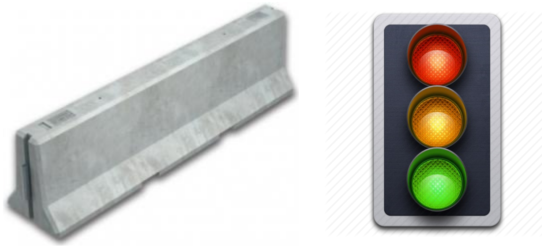
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2 →

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



shared sem_t arrival = 0

sem_t departure = 0

atomic int counter = 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 0 → if(--counter > 0)

CPU 1 → after the end of the first column

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2 → after the end of the second column

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

shared

```
sem_t arrival = 0
sem_t departure = 0
atomic int counter = 0
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = **1**

sem_t departure = **0**

atomic int counter = **0**

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

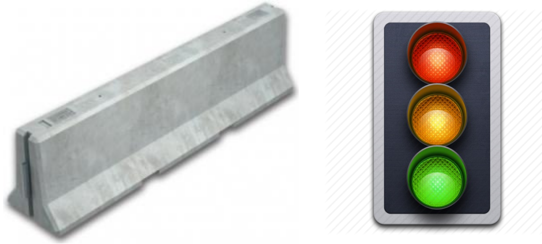
CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

Semaphore Barrier Action Zone

N == 3



```
shared    sem_t arrival = 1
          sem_t departure = 0
          atomic int counter = 0
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Still correct if counter is not atomic?

Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = 1

sem_t departure = 0

atomic int counter = 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

Do we need two phases?

Still correct if counter is not atomic?

Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = **1**
sem_t departure = **0**
atomic int counter = **0**

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(
if(++counte
  sem_pos
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
// why two phases:
for(…) {
    do_something();
    wait();
}
```

Do we need two phases?

Still correct if counter is not atomic?

Barrier using Semaphores

Properties

- Pros:

- Cons:

Barrier using Semaphores

Properties

- Pros:
  - Very Simple
  - Space complexity O(1)
  - Symmetric
- Cons:

Barrier using Semaphores

Properties

- Pros:
  - Very Simple
  - Space complexity O(1)
  - Symmetric
- Cons:
  - Required a strong object
    - Requires some central manager
    - High contention on the semaphores
  - Propagation delay O(n)

Barriers based on counters

Counter Barrier Ingredients

Fetch-and-Increment register

- A shared register that supports a F&I operation:
- Input: register *r*
- Atomic operation:
  - *r* is incremented by 1
  - the old value of r is returned

```
function fetch-and-increment (r : register)
    orig_r := r;
    r:= r + 1;
    return (orig_r);
end-function
```

Await

- For brevity, we use the **await** macro
- Not an operation of an object
- This is just “spinning”

```
macro await (condition : boolean condition)
    repeat
        cond = eval(condition);
    until (cond)
end-macro
```

Simple Barrier Using an Atomic Counter

```
shared    counter: fetch and increment reg. – {0,..n}, initially = 0
          go: atomic bit, initial value does not matter
local     local.go: a bit, initial value  does not matter
          local.counter: register
```

Simple Barrier Using an Atomic Counter

```
shared   counter: fetch and increment reg. – {0,..n}, initially = 0
         go: atomic bit, initial value does not matter
local    local.go: a bit, initial value  does not matter
         local.counter: register
```

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

shared	counter: fetch and increment reg. – {0,..n}, initially = 0
	go: atomic bit, initial value does not matter
local	local.go: a bit, initial value does not matter
	local.counter: register

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Pros/Cons?

Simple Barrier Using an Atomic Counter

```
shared    counter: fetch and increment reg. – {0,..n}, initially = 0
          go: atomic bit, initial value does not matter
local     local.go: a bit, initial value  does not matter
          local.counter: register
```

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Pros/Cons?

Simple Barrier Using an Atomic Counter

shared	counter: fetch and increment reg. – {0,..n}, initially = 0
	go: atomic bit, initial value does not matter
local	local.go: a bit, initial value does not matter
	local.counter: register

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Pros/Cons?

- There is high memory contention on *go* bit

Simple Barrier Using an Atomic Counter

```
shared  counter: fetch and increment reg. – {0,..n}, initially = 0
        go: atomic bit, initial value does not matter
local   local.go: a bit, initial value  does not matter
        local.counter: register
```

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Pros/Cons?

- There is high memory contention on *go* bit
- Reducing the contention:
  - Replace the *go* bit with *n* bits: *go*[1],…,*go*[*n*]
  - Process p_i may spin only on the bit *go*[*i*]

A Local Spinning Counter Barrier

Program of a Thread i

```
shared   counter: fetch and increment reg. – {0,..n}, initially = 0
         go[1..n]: array of atomic bits, initial values are immaterial
local    local.go: a bit, initial value is immaterial
         local.counter: register
```

A Local Spinning Counter Barrier

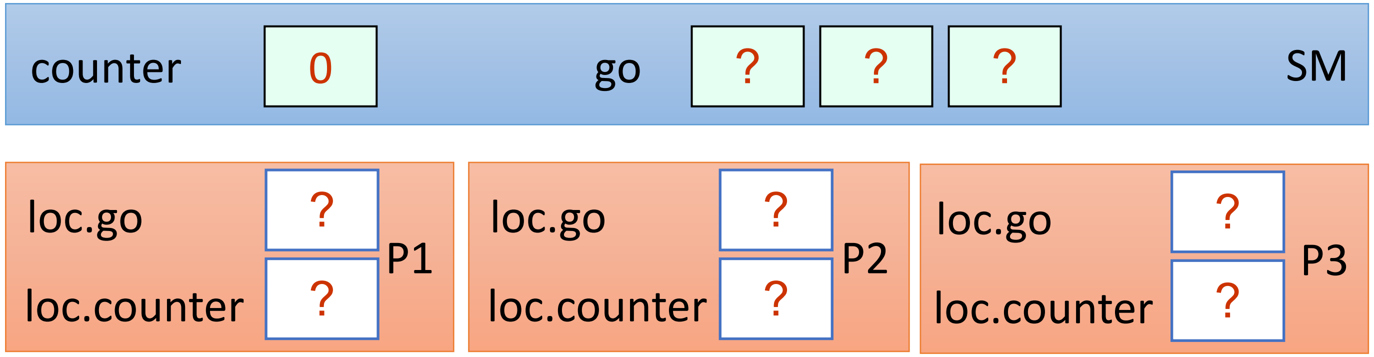
Program of a Thread i

shared	counter: fetch and increment reg. – {0,..n}, initially = 0
	go[1..n]: array of atomic bits, initial values are immaterial
local	local.go: a bit, initial value is immaterial
	local.counter: register

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0

go ? ? ?

SM

loc.go ?

loc.counter ?

P1

loc.go ?

loc.counter ?

P2

loc.go ?

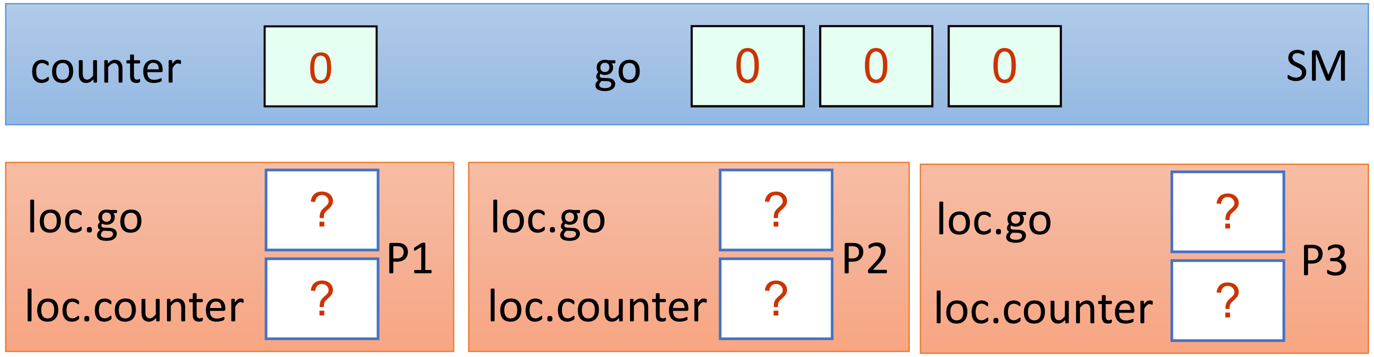
loc.counter ?

P3

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

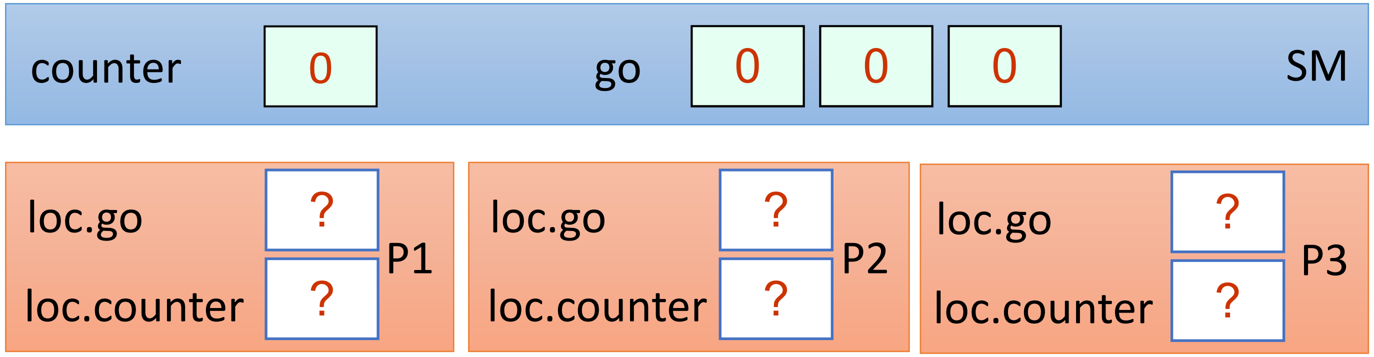
Example Run for n=3 Threads



```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go 0 0 0 SM

loc.go ? loc.counter ? P1

loc.go ? loc.counter ? P2

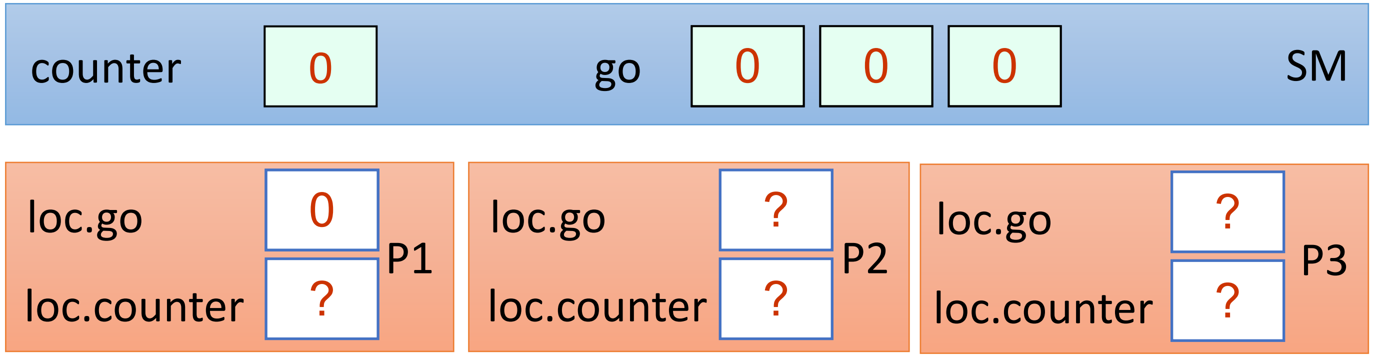
loc.go ? loc.counter ? P3

P1 →

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

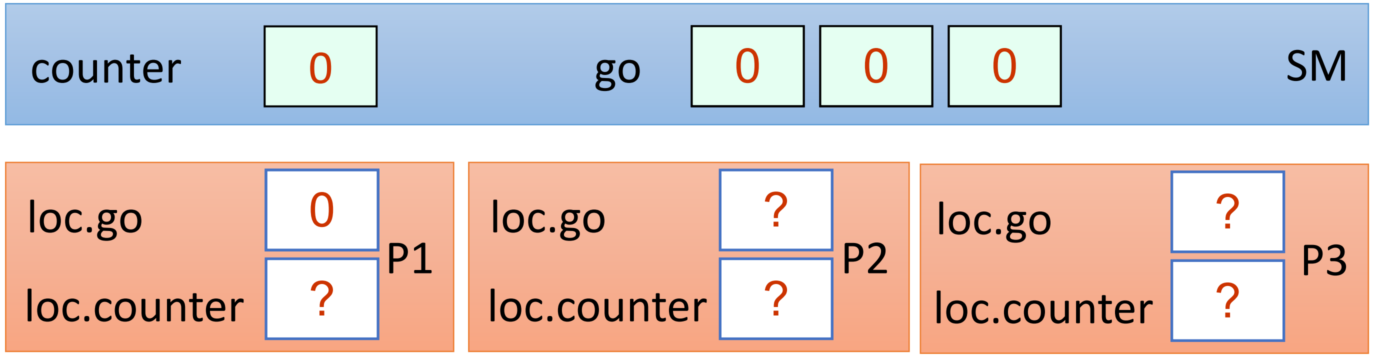
Example Run for n=3 Threads



```
P1 →
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0

go 0 0 0

SM

loc.go 0

loc.counter ?

P1

loc.go ?

loc.counter ?

P2

loc.go ?

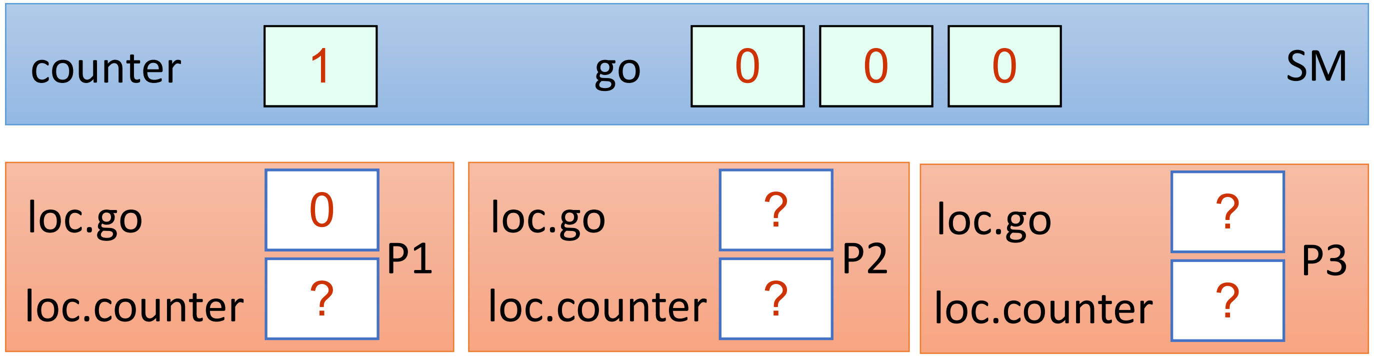
loc.counter ?

P3

```
      local.go := go[i]
P1 →  local.counter := fetch-and-increment (counter)
      **if** local.counter + 1 = n **then**
          counter := 0
          **for** j=1 **to** n { go[j] := 1 – go[j] }
      **else await**(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 1

go 0 0 0

SM

loc.go 0
loc.counter ?
P1

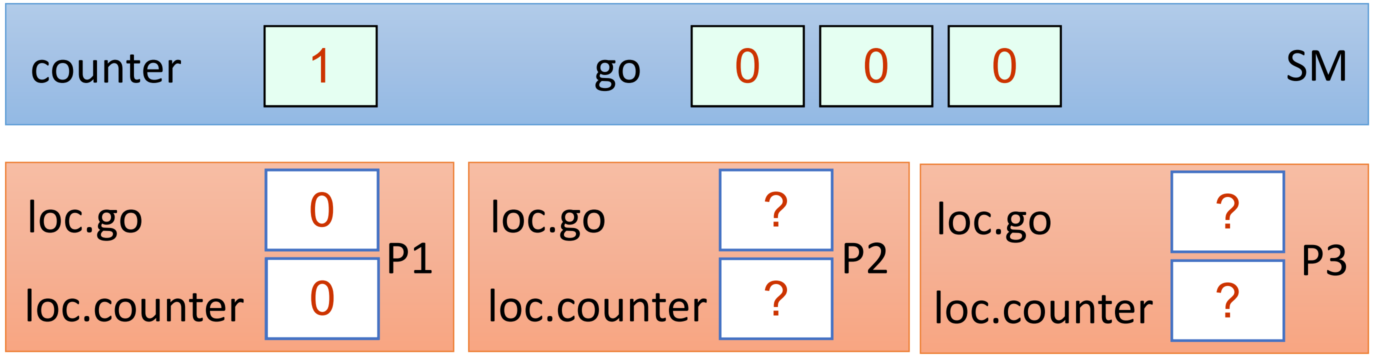
loc.go ?
loc.counter ?
P2

loc.go ?
loc.counter ?
P3

```
      local.go := go[i]
P1 →  local.counter := fetch-and-increment (counter)
      if local.counter + 1 = n then
          counter := 0
          for j=1 to n { go[j] := 1 – go[j] }
      else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



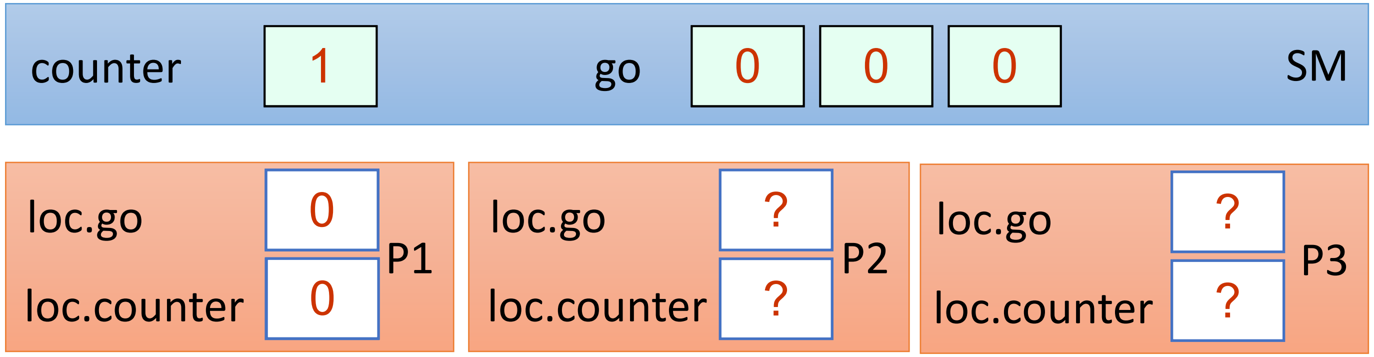
counter	1	go	0	0	0	SM

loc.go	0	P1	loc.go	?	P2	loc.go	?	P3
loc.counter	0		loc.counter	?		loc.counter	?	

```
     1   local.go := go[i]
P1 → 2   local.counter := fetch-and-increment (counter)
     3   if local.counter + 1 = n then
     4       counter := 0
     5       for j=1 to n { go[j] := 1 – go[j] }
     6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

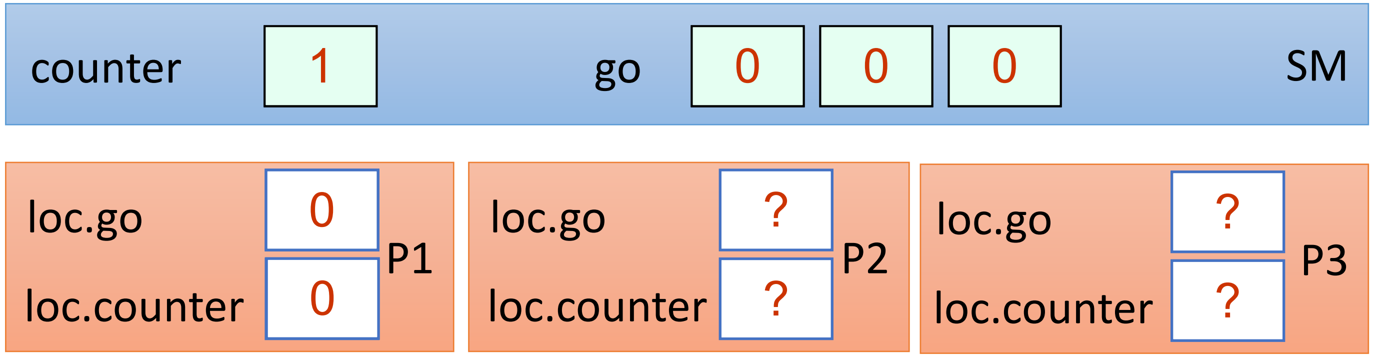
Example Run for n=3 Threads



```
     1   local.go := go[i]
     2   local.counter := fetch-and-increment (counter)
P1 → 3   if local.counter + 1 = n then
     4       counter := 0
     5       for j=1 to n { go[j] := 1 – go[j] }
     6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



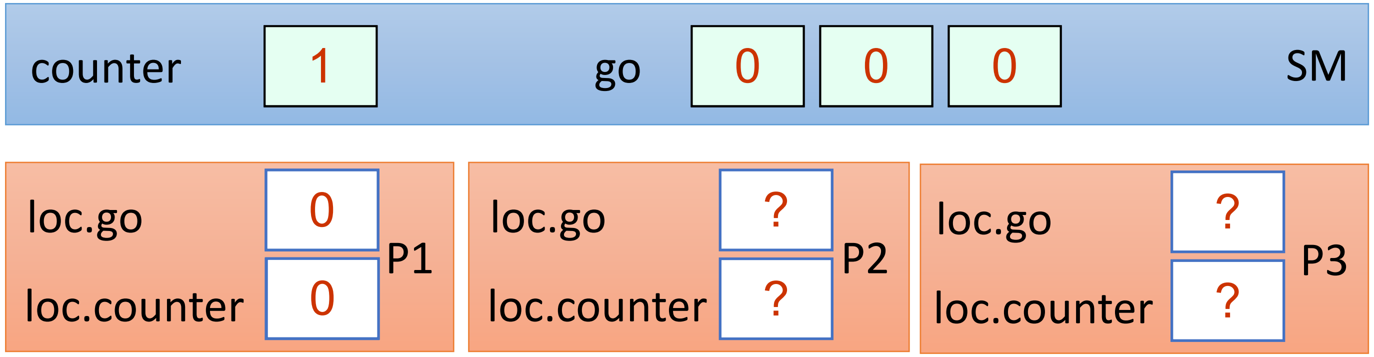
P1 →

```
1   local.go := go[i]
2   local.counter := fetch-and-increment (
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

0+1≠3

A Local Spinning Counter Barrier

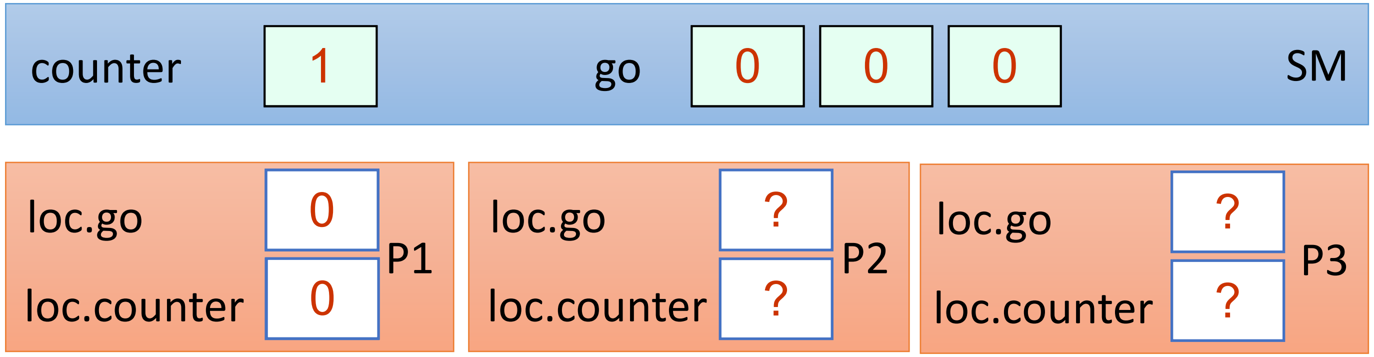
Example Run for n=3 Threads



```
     1   local.go := go[i]
     2   local.counter := fetch-and-increment (counter)
     3   if local.counter + 1 = n then
     4       counter := 0
     5       for j=1 to n { go[j] := 1 – go[j] }
P1 → 6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



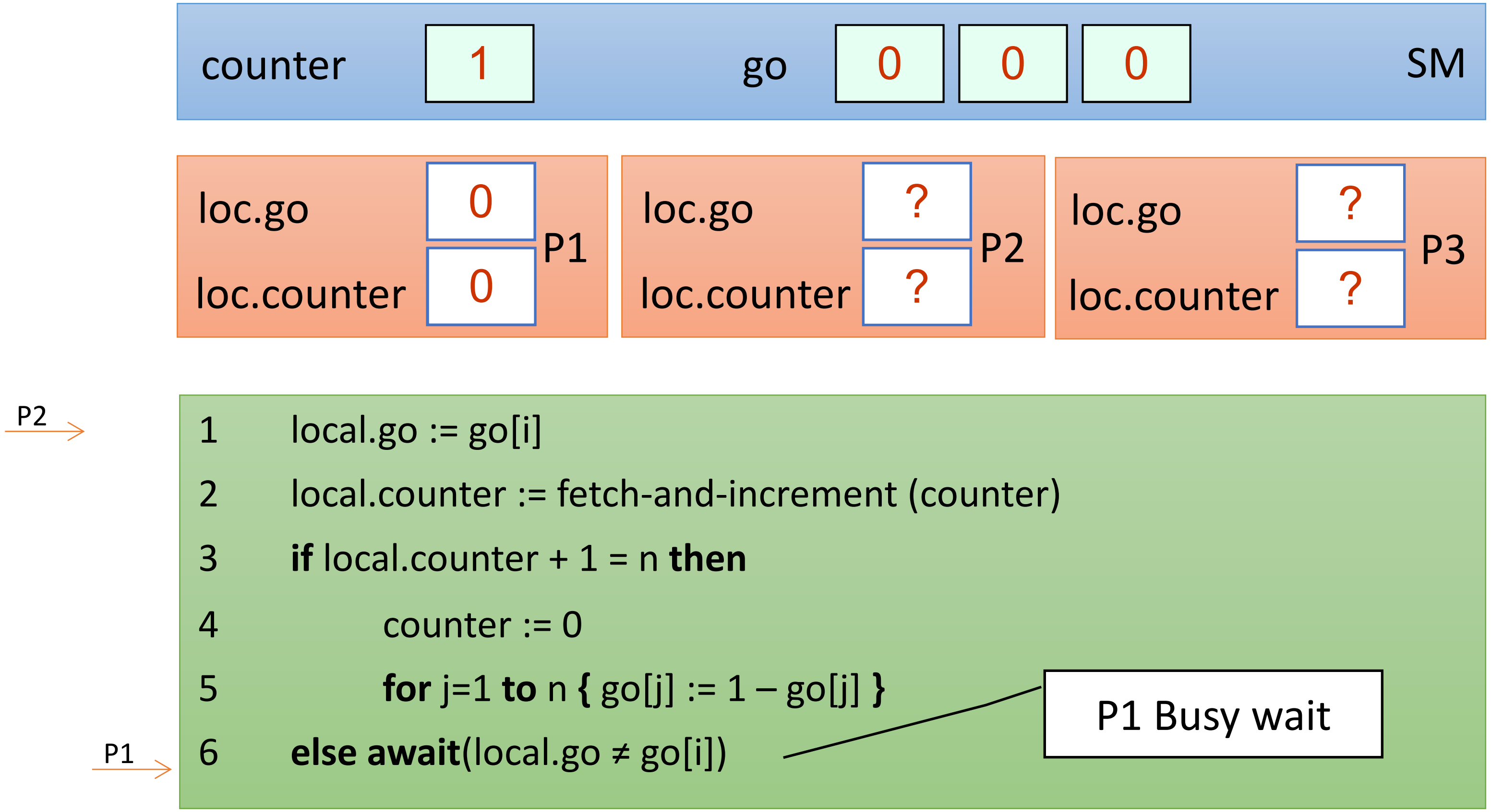
```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1

P1 Busy wait

A Local Spinning Counter Barrier

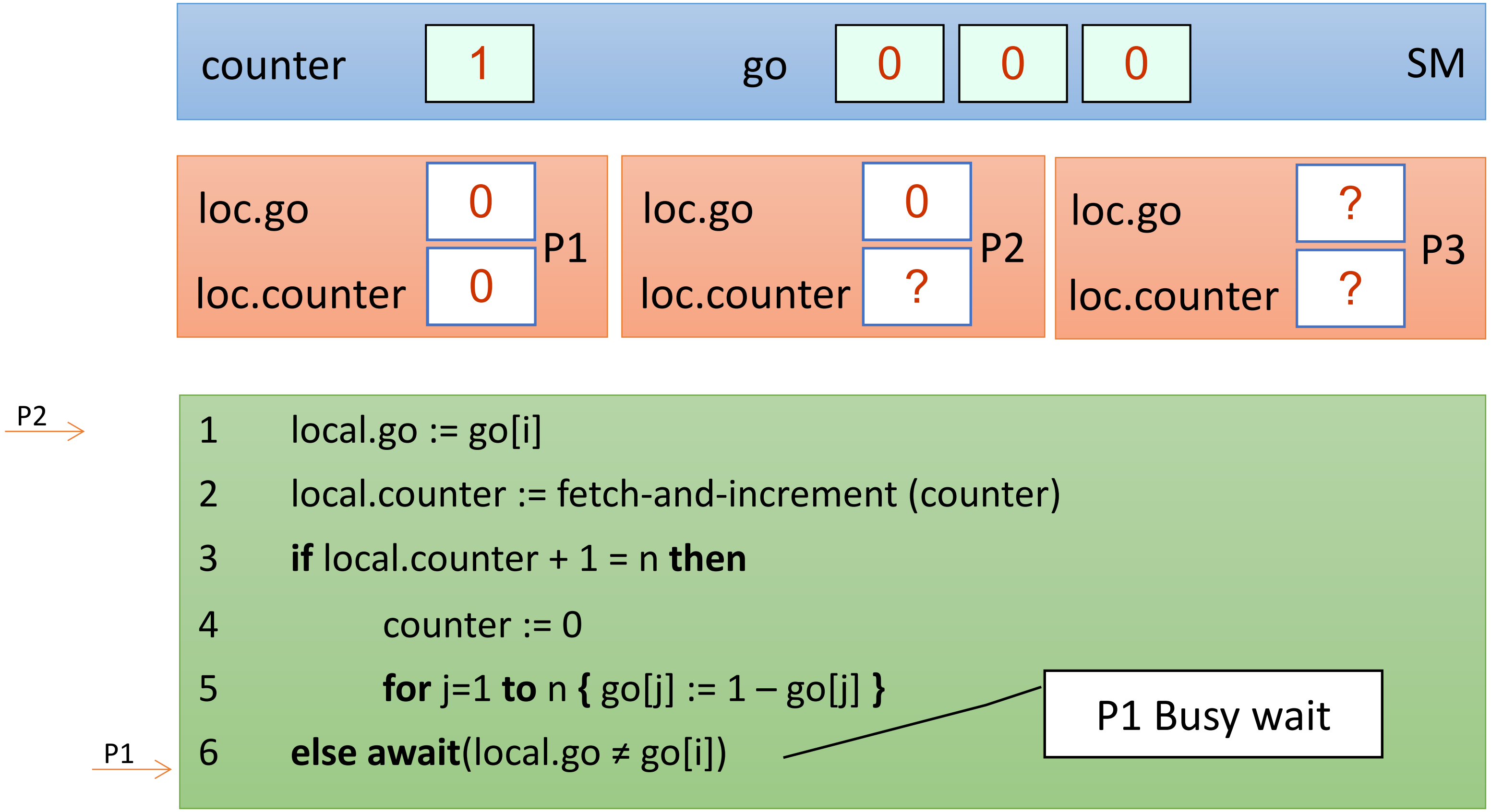
Example Run for n=3 Threads



```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 1 go 0 0 0 SM

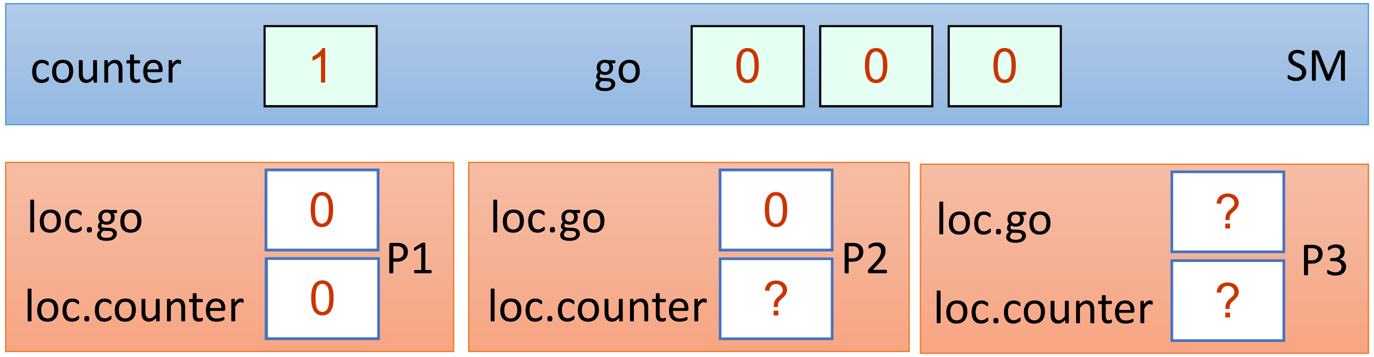
P1	loc.go	0
	loc.counter	0
P2	loc.go	0
	loc.counter	?
P3	loc.go	?
	loc.counter	?

```
P2 → 1   local.go := go[i]
     2   local.counter := fetch-and-increment (counter)
     3   if local.counter + 1 = n then
     4       counter := 0
     5       for j=1 to n { go[j] := 1 – go[j] }
P1 → 6   else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM: counter 1 | go 0 0 0

P1: loc.go 0 | loc.counter 0

P2: loc.go 0 | loc.counter ?

P3: loc.go ? | loc.counter ?

```
      1   local.go := go[i]
P2 →  2   local.counter := fetch-and-increment (counter)
      3   if local.counter + 1 = n then
      4       counter := 0
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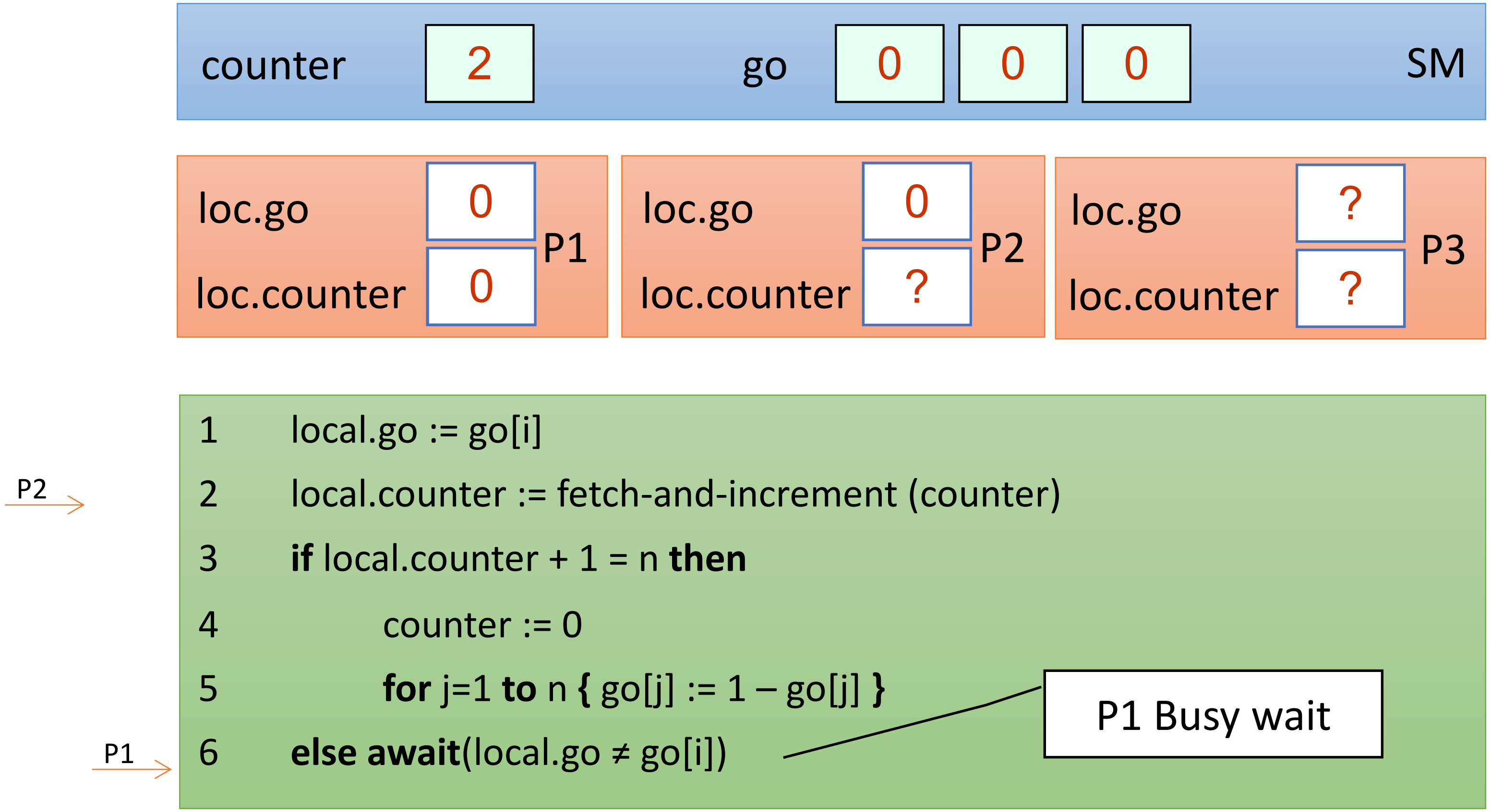
P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

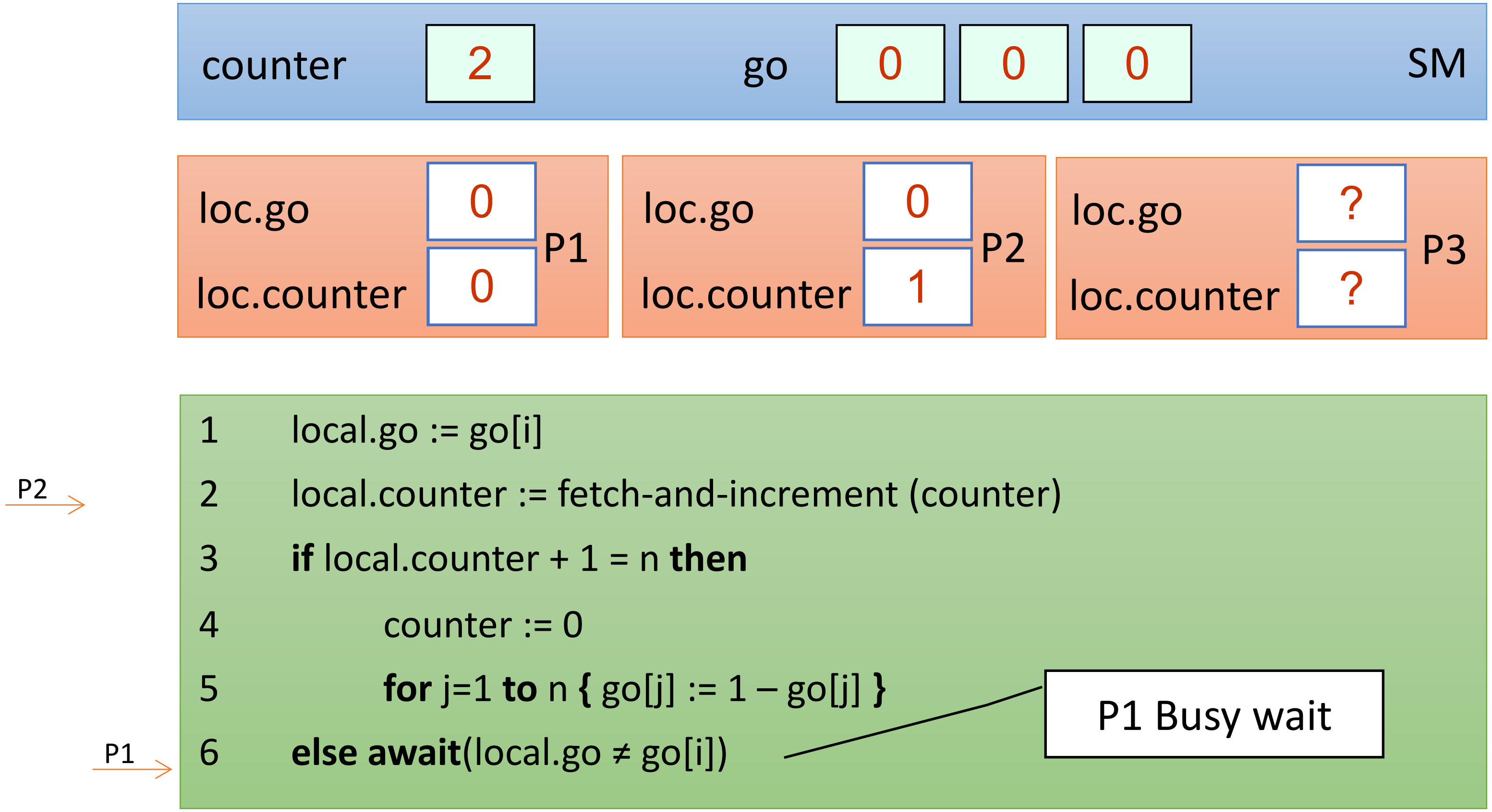


```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

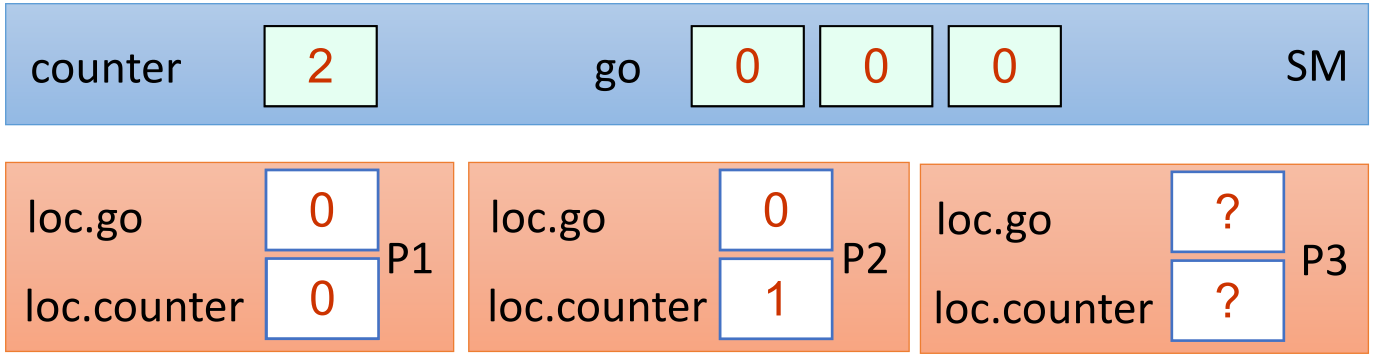


```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter	2	go	0	0	0

SM

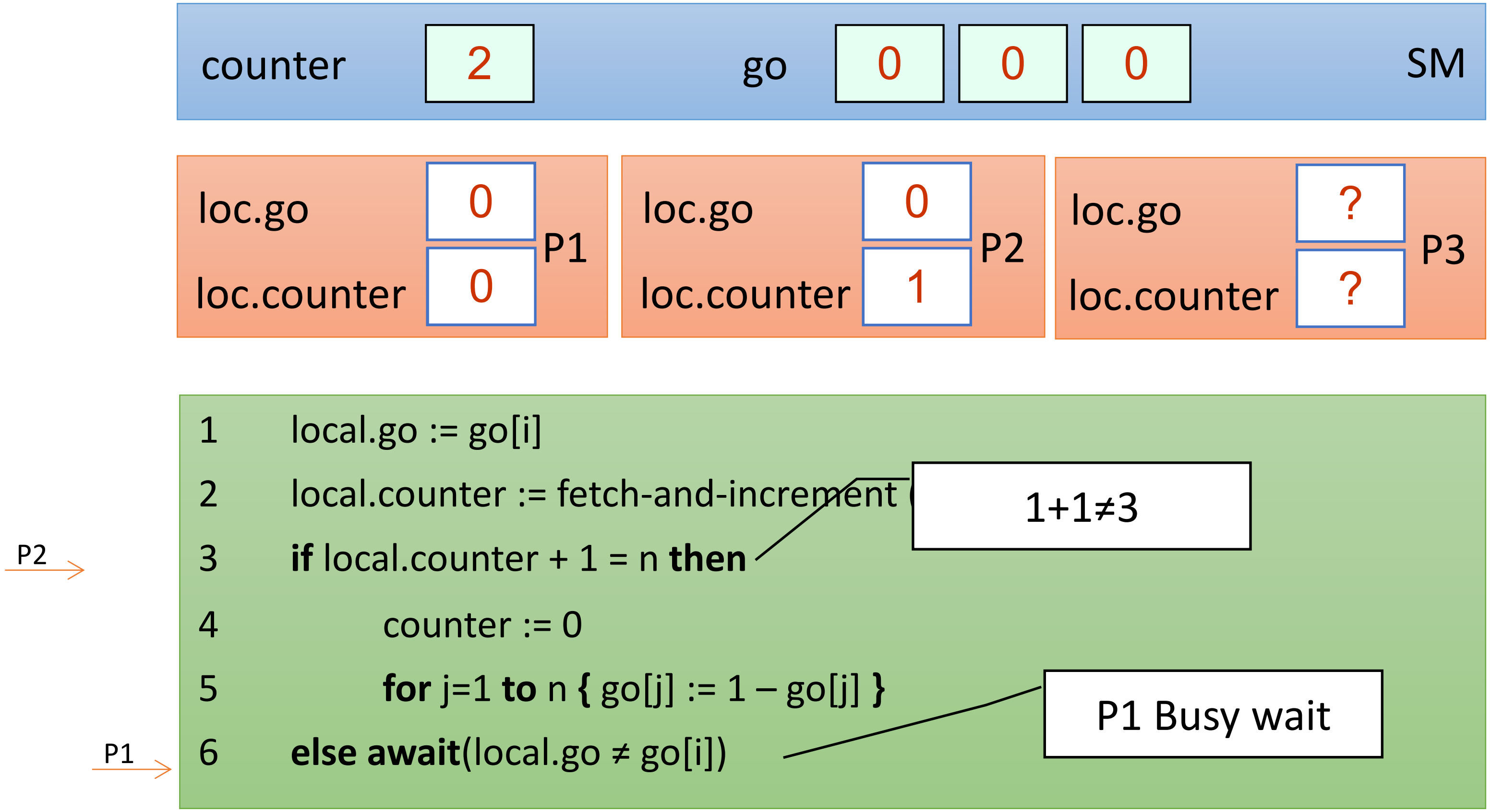
	P1	P2	P3
loc.go	0	0	?
loc.counter	0	1	?

```
   1  local.go := go[i]
   2  local.counter := fetch-and-increment (counter)
P2 → 3  if local.counter + 1 = n then
   4      counter := 0
   5      for j=1 to n { go[j] := 1 – go[j] }
P1 → 6  else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter	2	go	0	0	0

	P1	P2	P3
loc.go	0	0	?
loc.counter	0	1	?

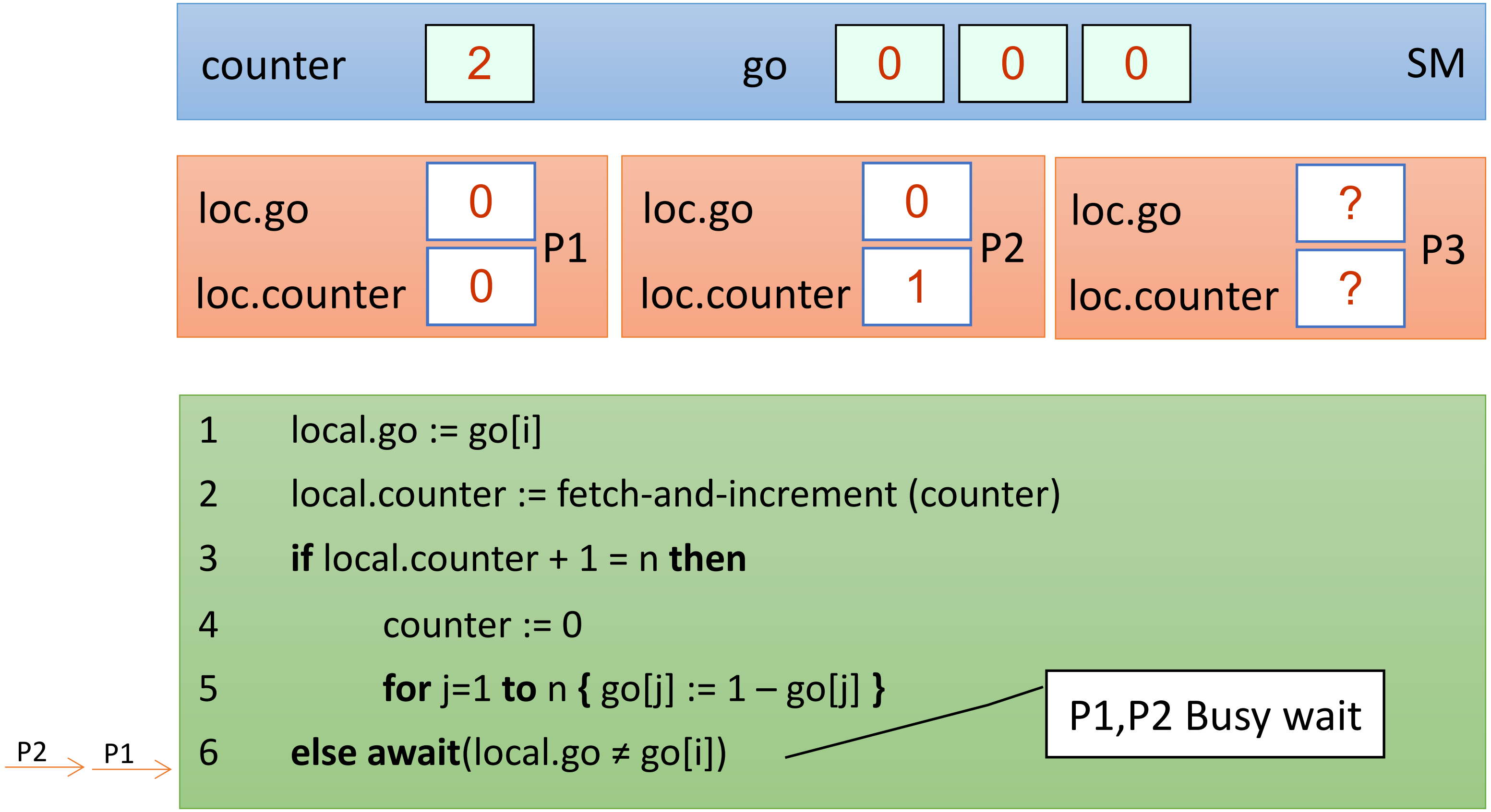
```
local.go := go[i]
local.counter := fetch-and-increment (
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

1+1≠3

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM: counter 2, go 0 0 0

P1: loc.go 0, loc.counter 0

P2: loc.go 0, loc.counter 1

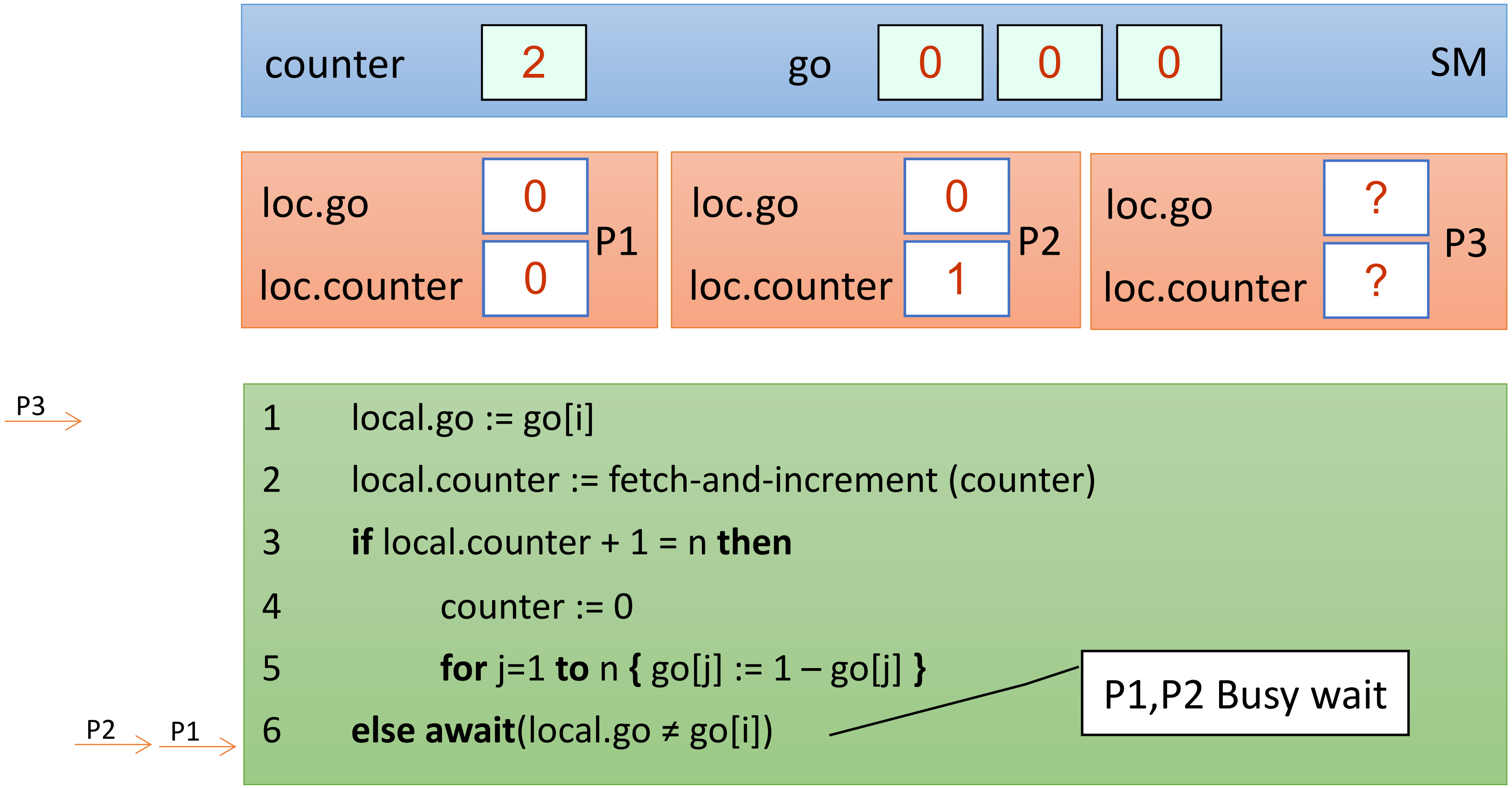
P3: loc.go ?, loc.counter ?

```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

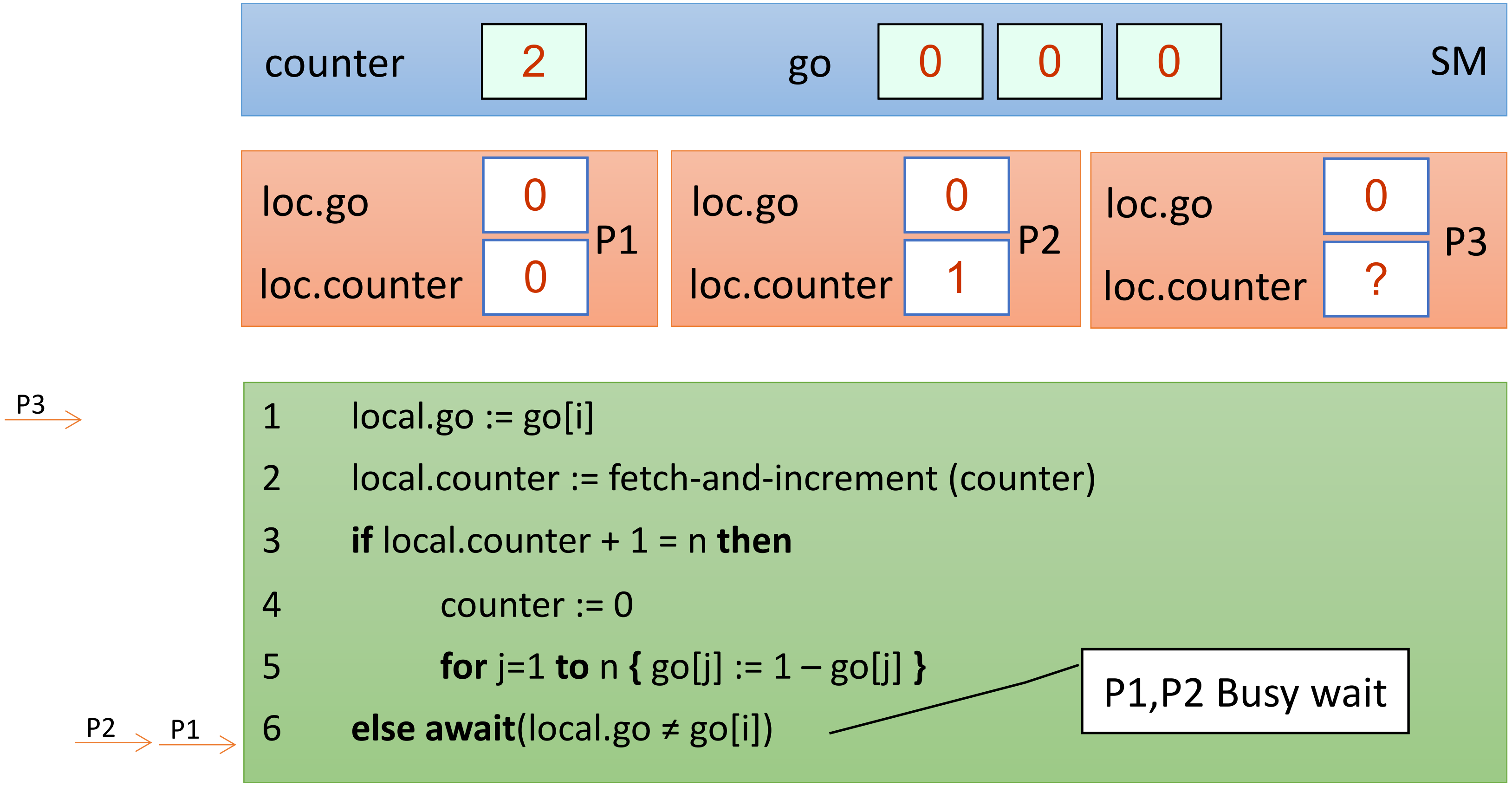
Example Run for n=3 Threads



```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads

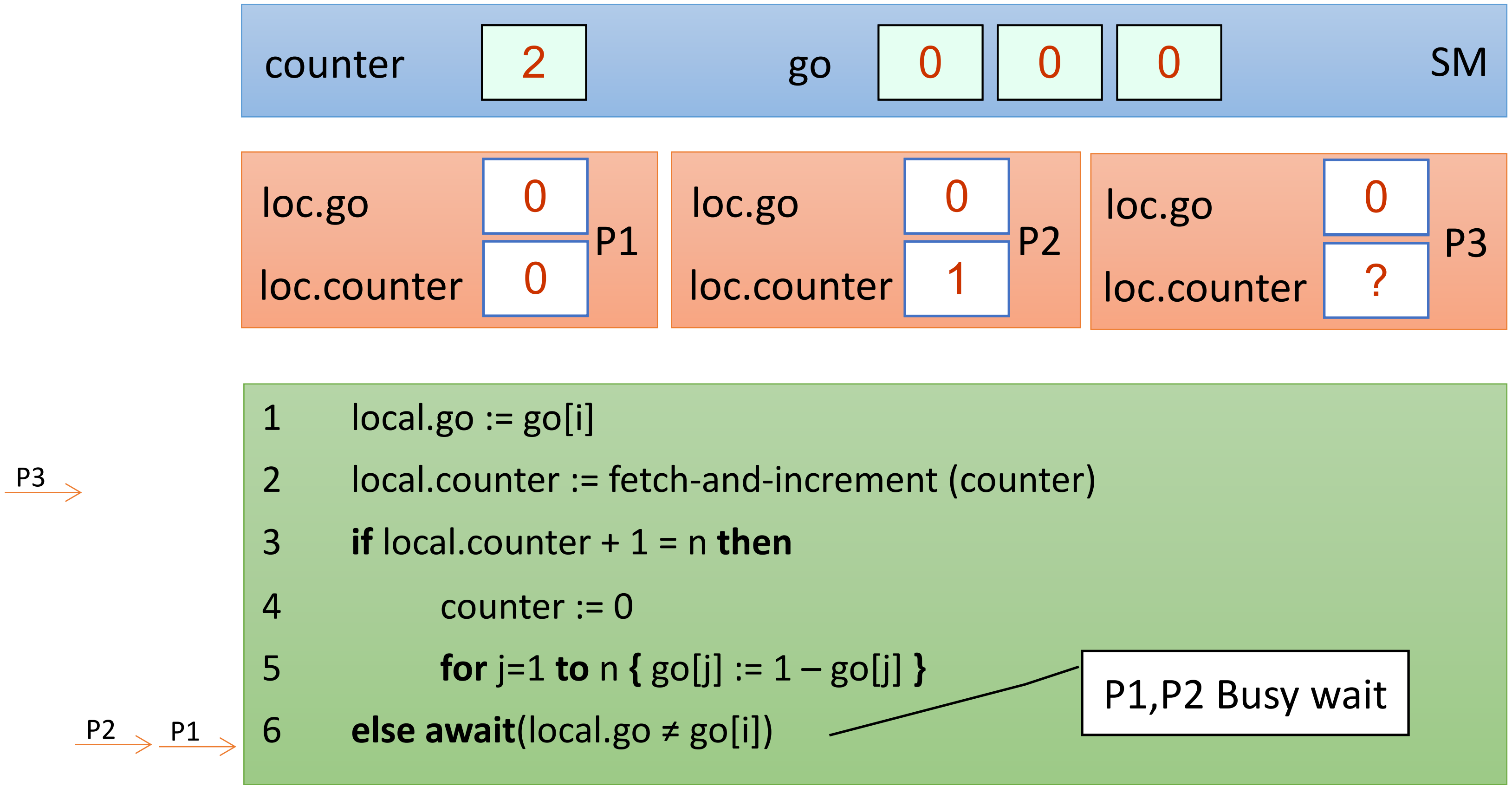


```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

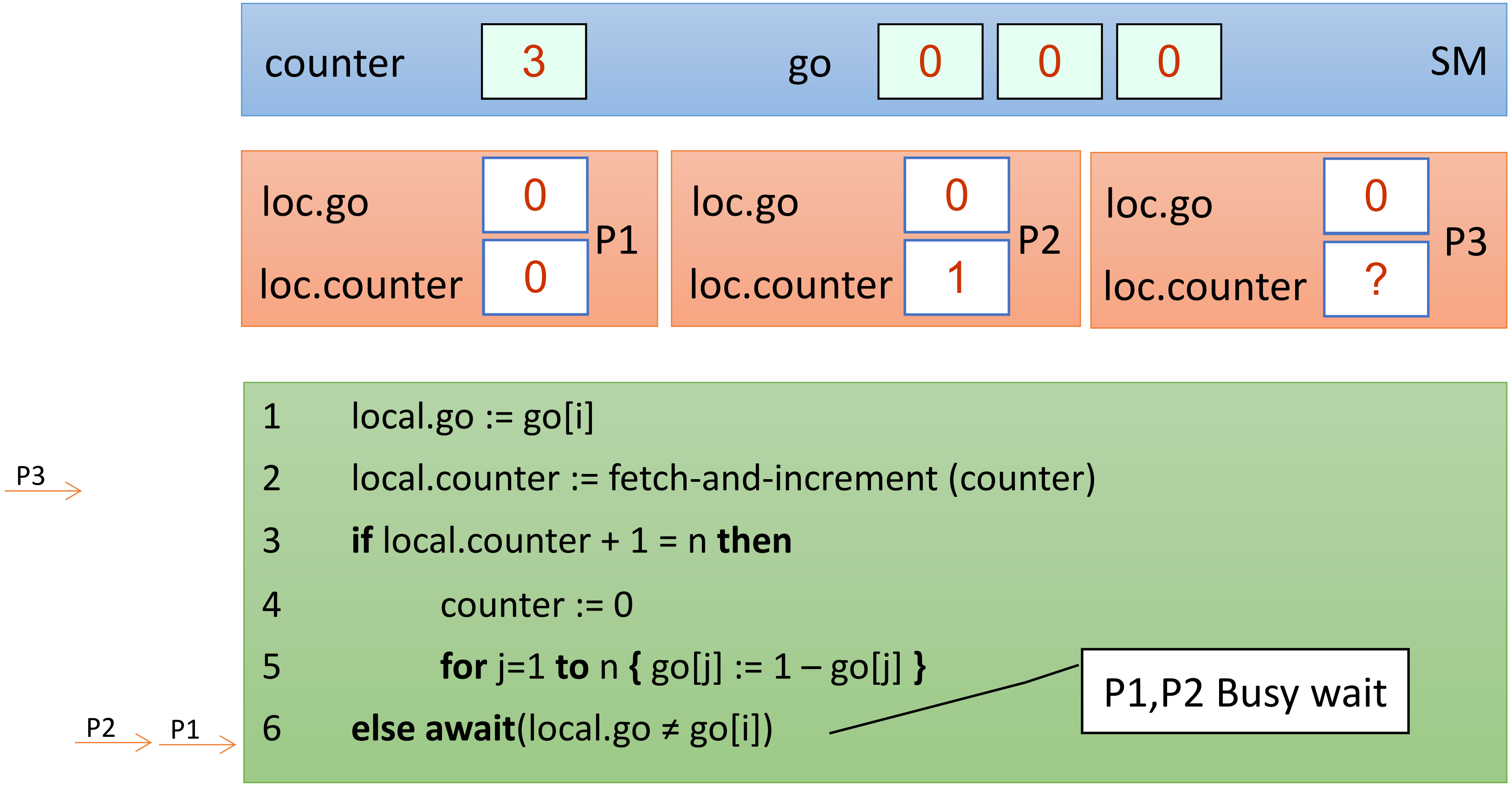


```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

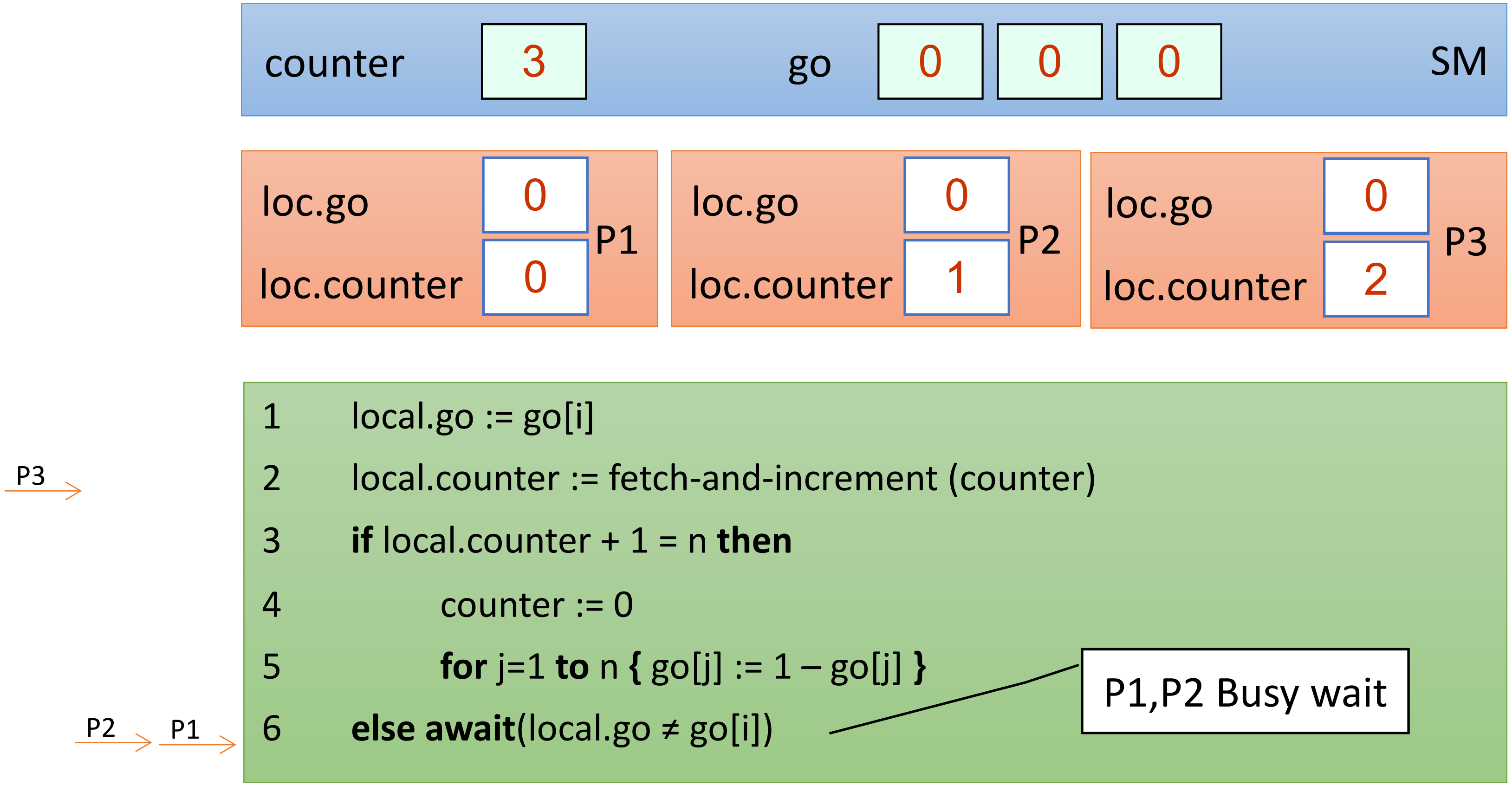


```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4           counter := 0
5           for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter	3	go	0	0	0

SM

loc.go	0		loc.go	0		loc.go	0
loc.counter	0	P1	loc.counter	1	P2	loc.counter	2

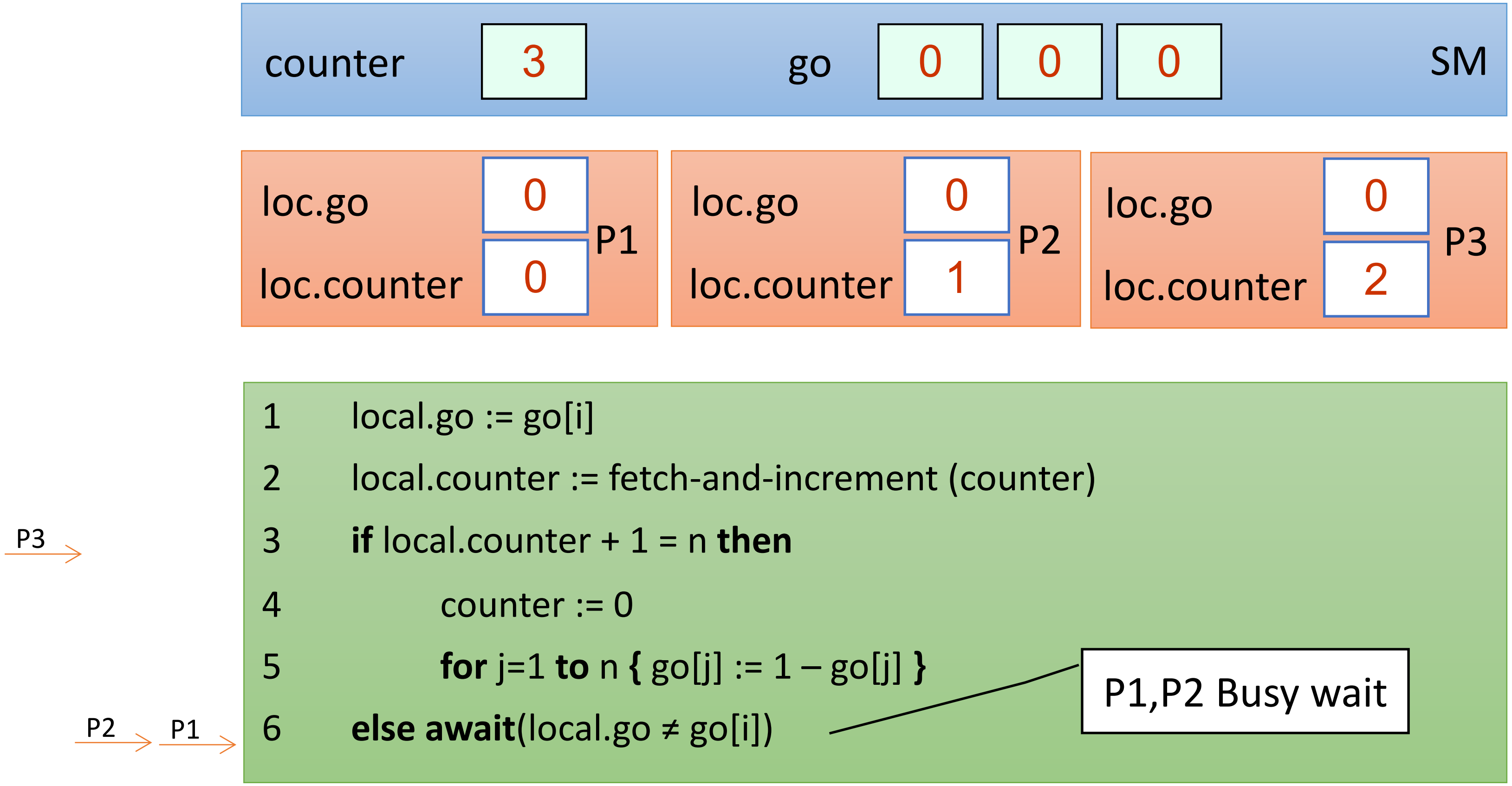
P3

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 3 go 0 0 0 SM

P1: loc.go 0, loc.counter 0

P2: loc.go 0, loc.counter 1

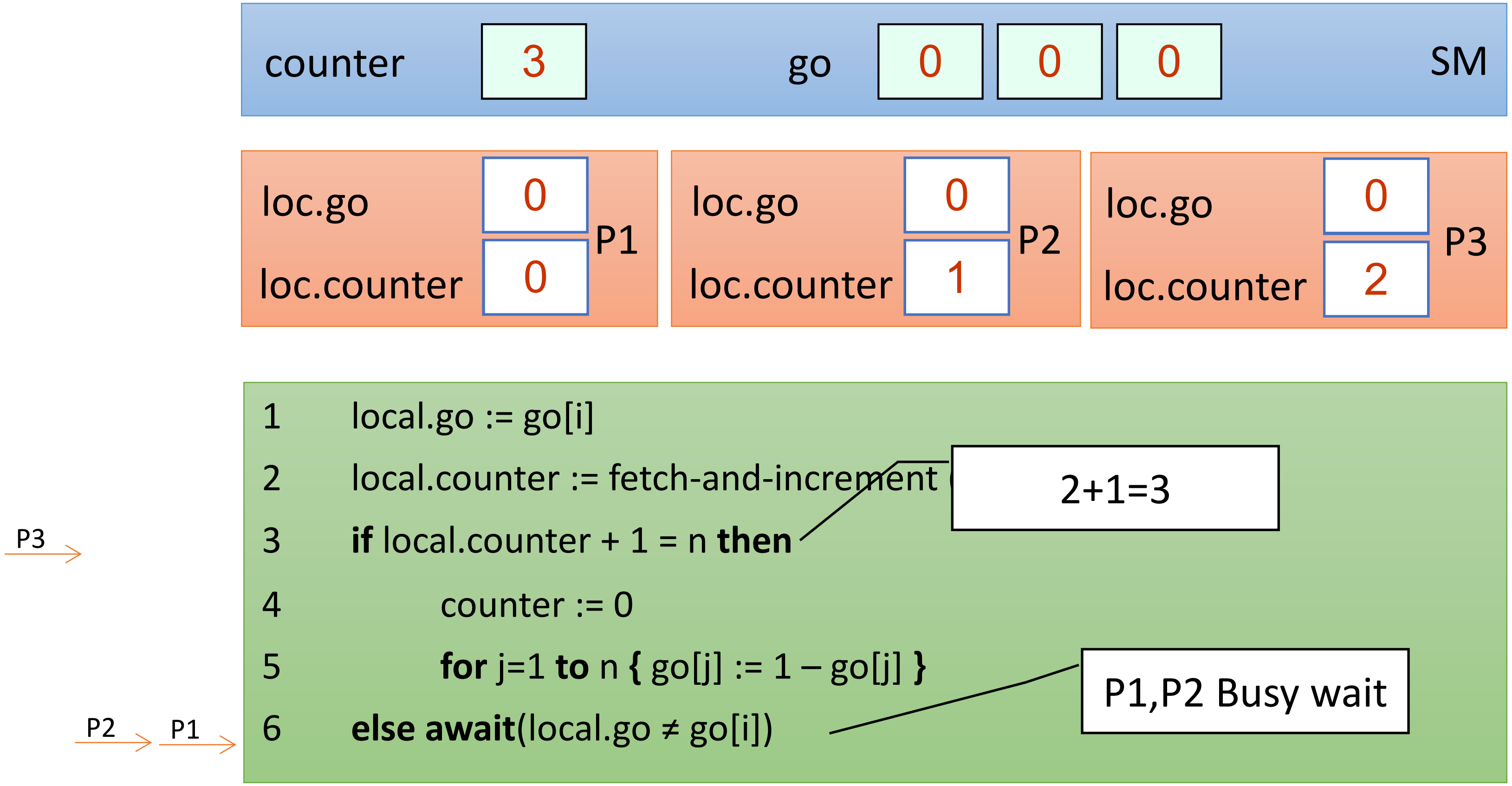
P3: loc.go 0, loc.counter 2

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



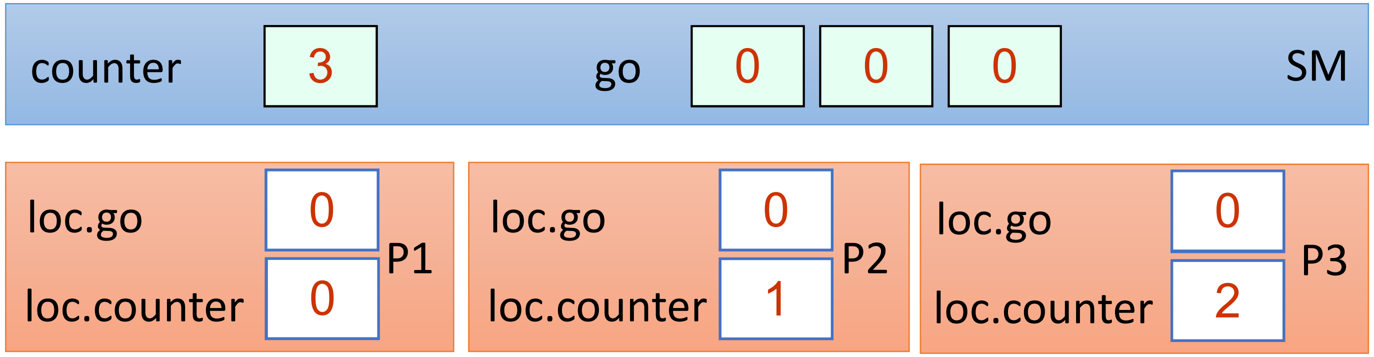
```
local.go := go[i]
local.counter := fetch-and-increment
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

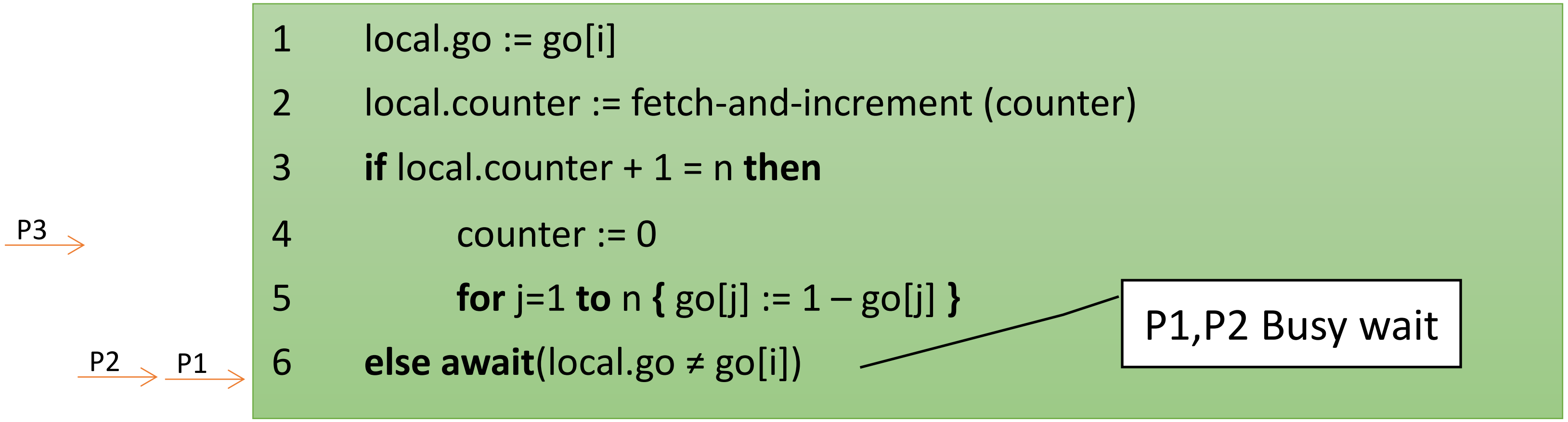
2+1=3

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads





```
1    local.go := go[i]
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3    if local.counter + 1 = n then
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6    else await(local.go ≠ go[i])
```
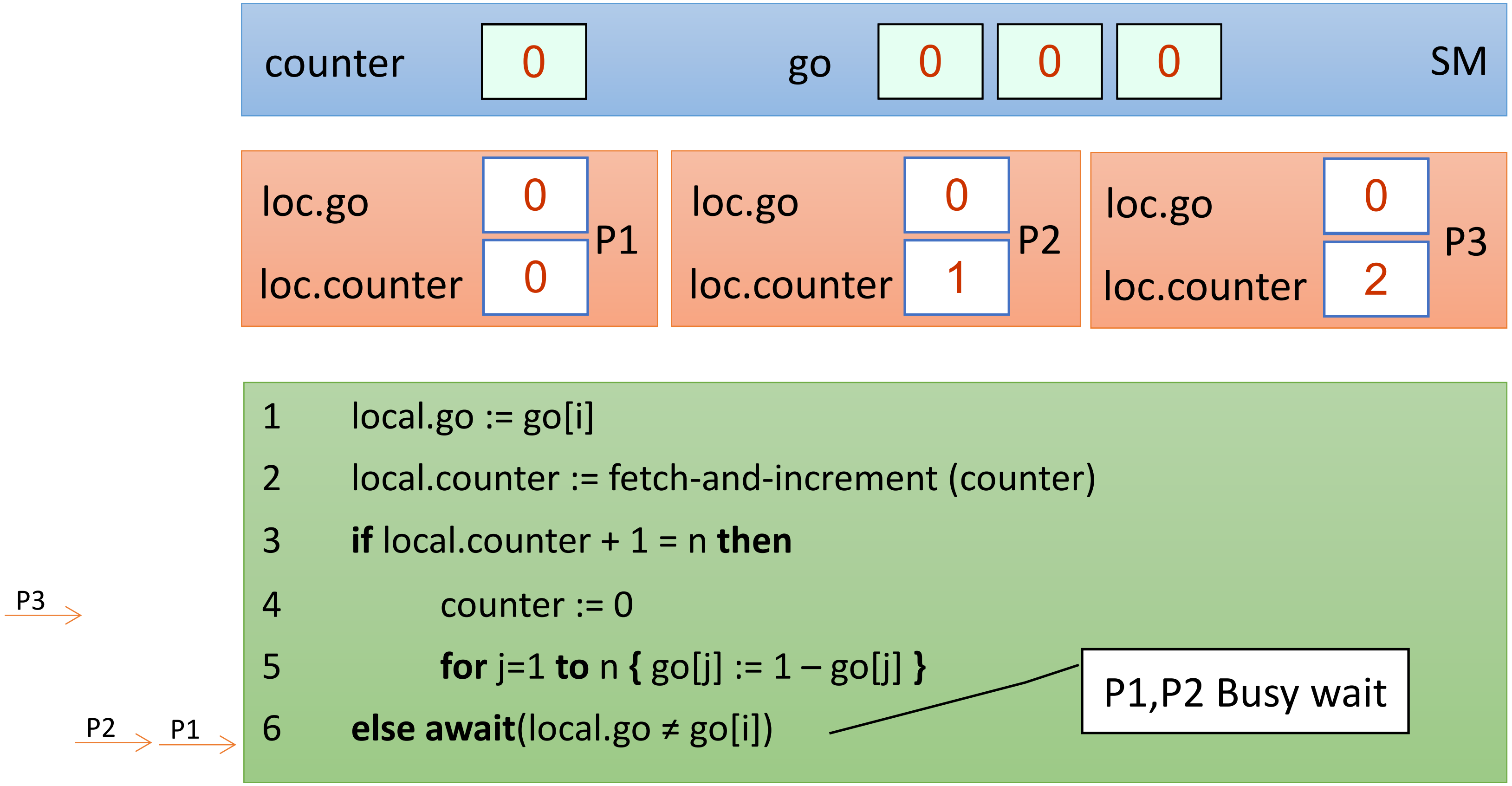

A Local Spinning Counter Barrier

Example Run for n=3 Threads

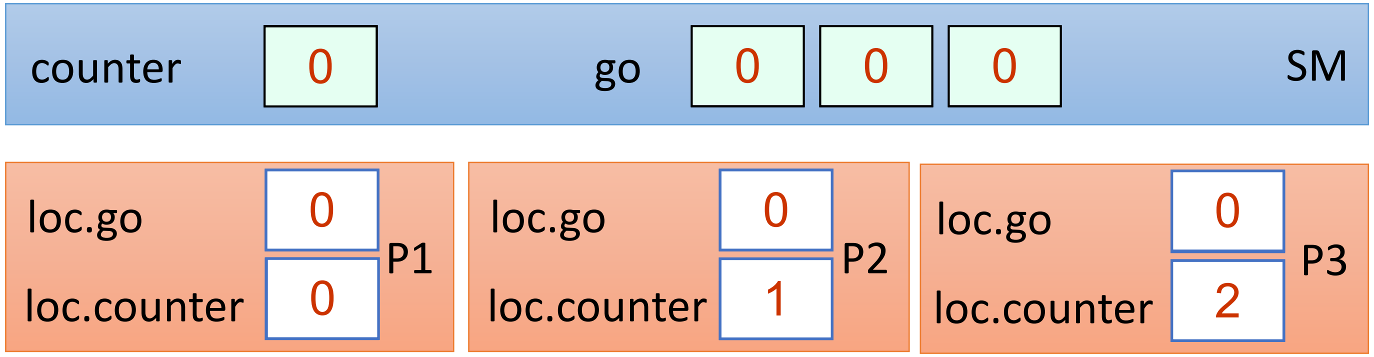


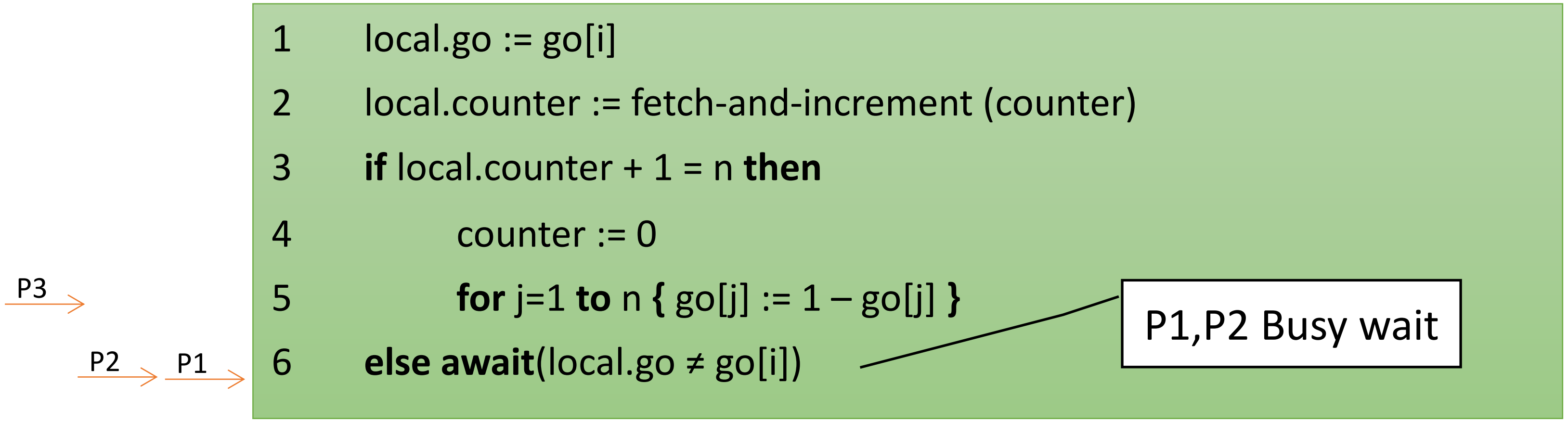
```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



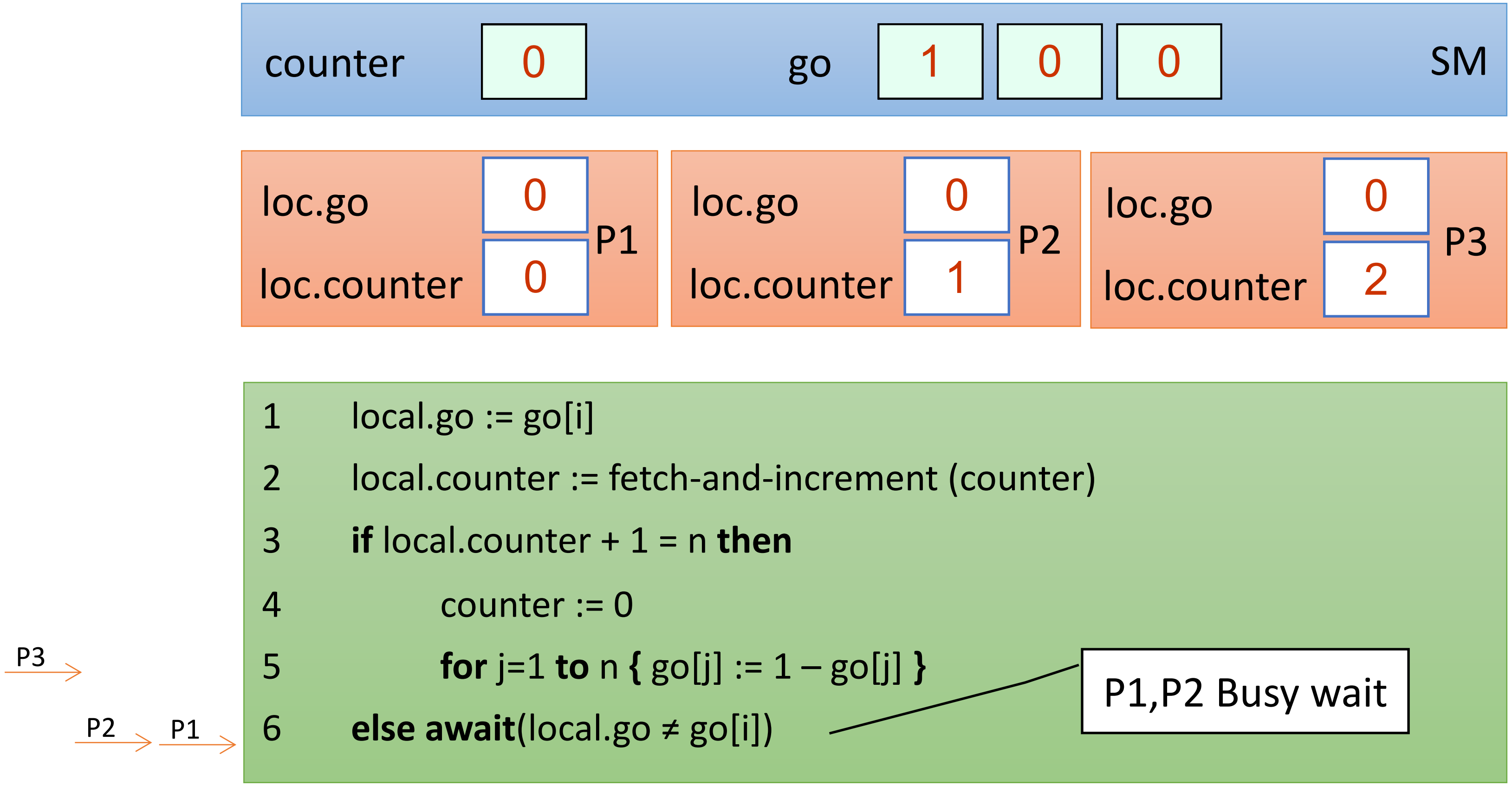


```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM: counter 0 go 1 0 0

P1: loc.go 0 loc.counter 0

P2: loc.go 0 loc.counter 1

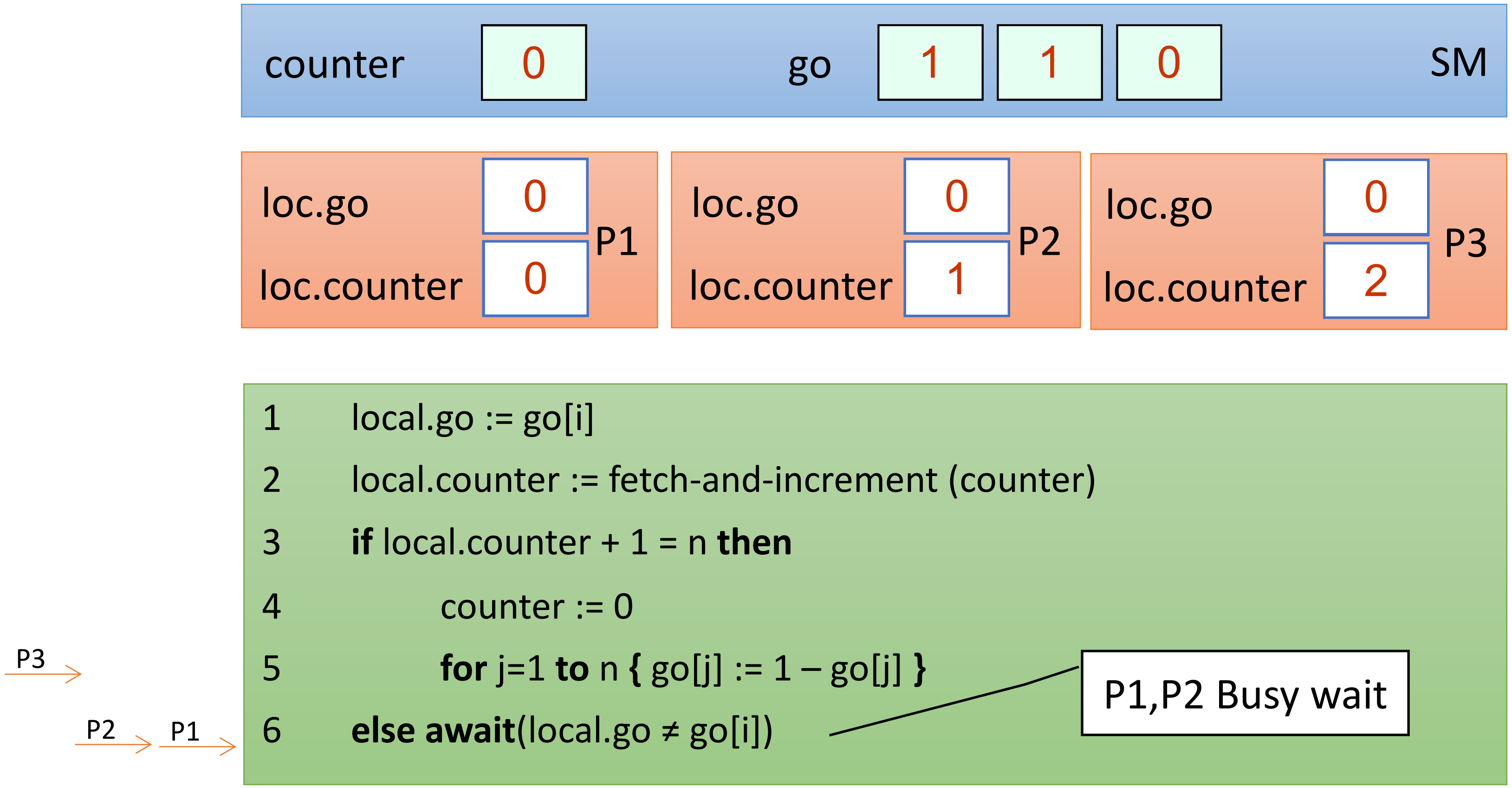
P3: loc.go 0 loc.counter 2

```
1     local.go := go[i]
2     local.counter := fetch-and-increment (counter)
3     if local.counter + 1 = n then
4           counter := 0
5           for j=1 to n { go[j] := 1 – go[j] }        <- P3
6     else await(local.go ≠ go[i])                     <- P2, P1
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM: counter 0; go 1 1 0

P1: loc.go 0; loc.counter 0

P2: loc.go 0; loc.counter 1

P3: loc.go 0; loc.counter 2

```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
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5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
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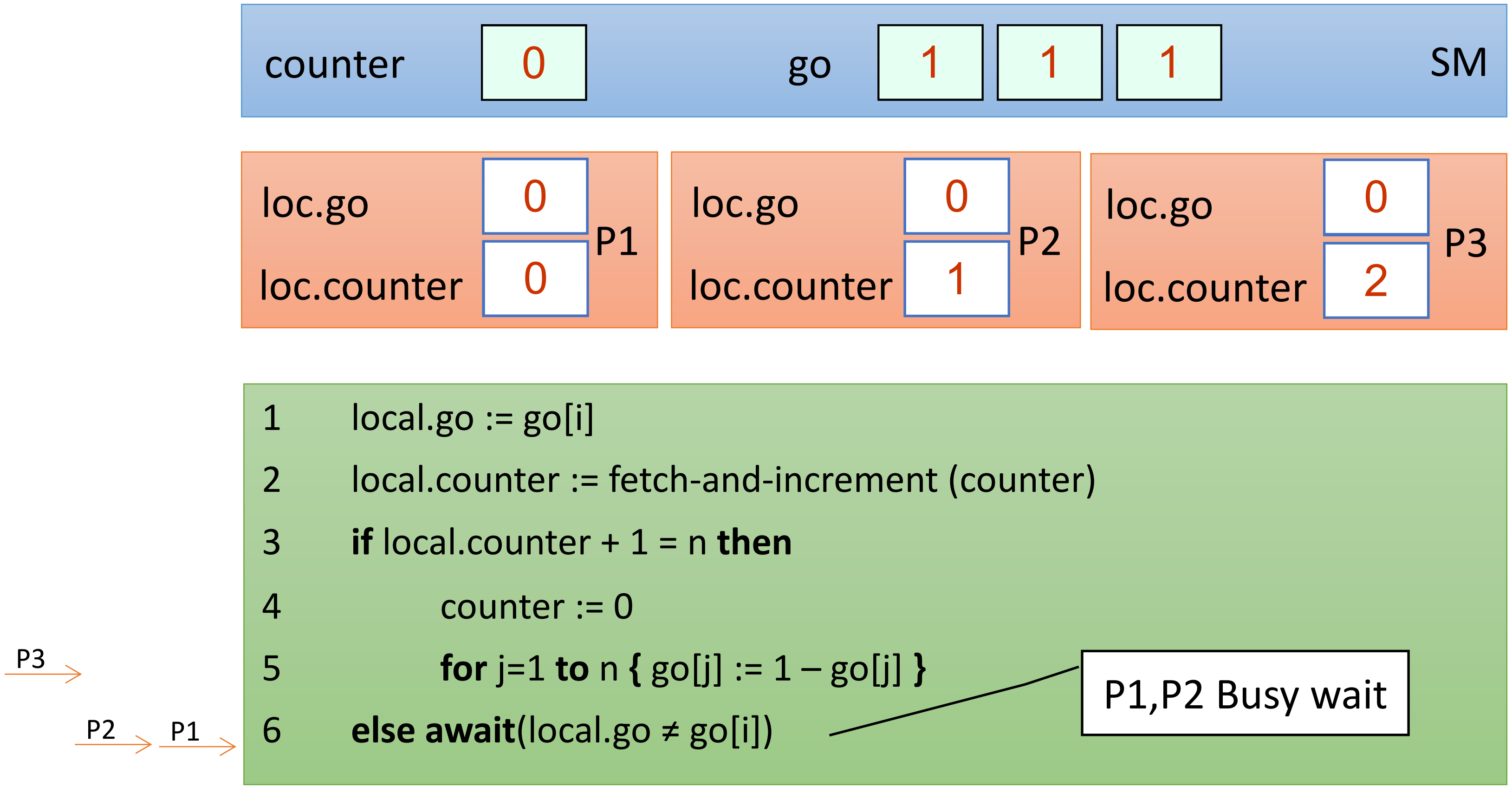
P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go 1 1 1 SM

	P1	P2	P3
loc.go	0	0	0
loc.counter	0	1	2

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

SM

counter 0

go 1 1 1

P1

loc.go 0

loc.counter 0

P2

loc.go 0

loc.counter 1

P3

loc.go 0

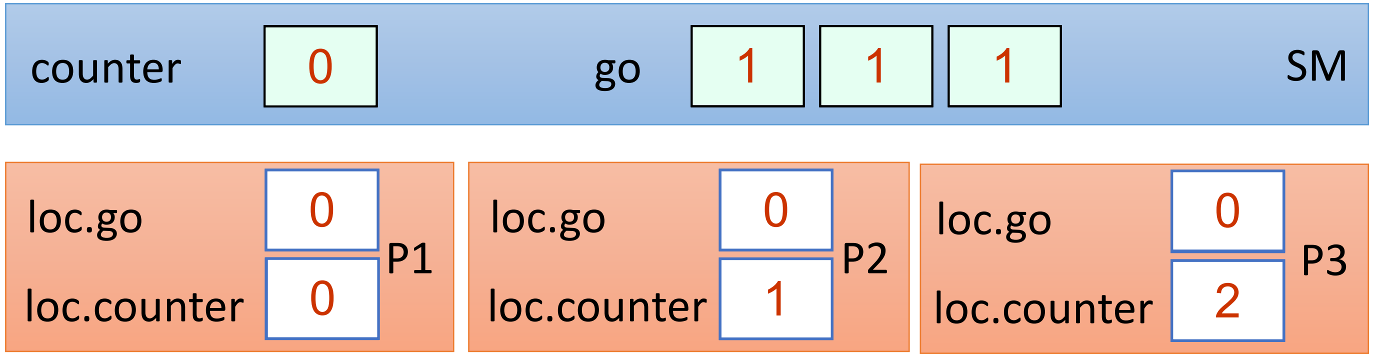
loc.counter 2

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P3 → P2 → P1

A Local Spinning Counter Barrier

Example Run for n=3 Threads



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local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

Pros/Cons?
Does this actually reduce contention?

Comparison of counter-based Barriers

Simple Barrier

- Pros:
- Cons:

Simple Barrier with go array

- Pros:
- Cons:

Comparison of counter-based Barriers

Simple Barrier

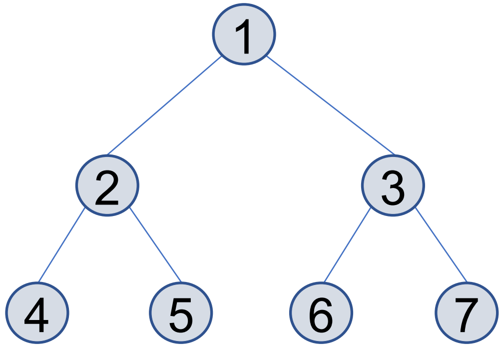
- Pros:
    - Very Simple
    - Shared memory: O(log n) ***bits***
    - Takes O(1) until last waiting p is awaken
- Cons:
    - High contention on the go bit
    - Contention on the counter register (*)

Simple Barrier with go array

- Pros:
    - Low contention on the go array
    - In some models:
        - spinning is done on local memory
        - remote mem. ref.: O(1)
- Cons:
    - Shared memory: O(n)
    - Still contention on the counter register (*)
    - Takes O(n) until last waiting p is awaken

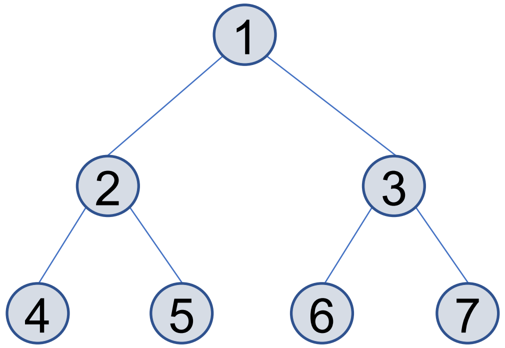
Tree Barriers

A Tree-based Barrier



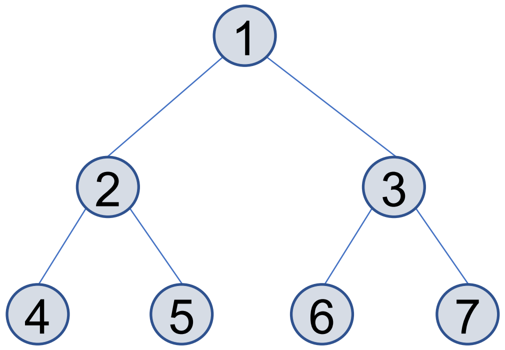
A Tree-based Barrier

- Threads are organized in a binary tree
- Each node is owned by a predetermined thread



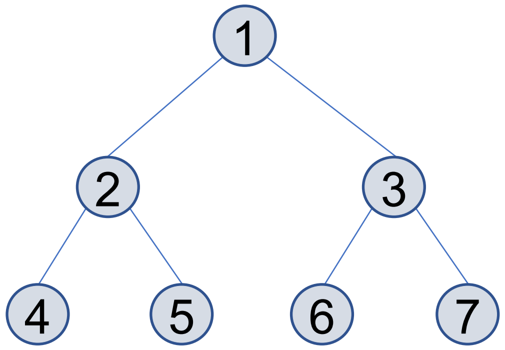
A Tree-based Barrier

- Threads are organized in a binary tree
- Each node is owned by a predetermined thread
- Each thread waits until its 2 children arrive
  - combines results
  - passes them on to its parent

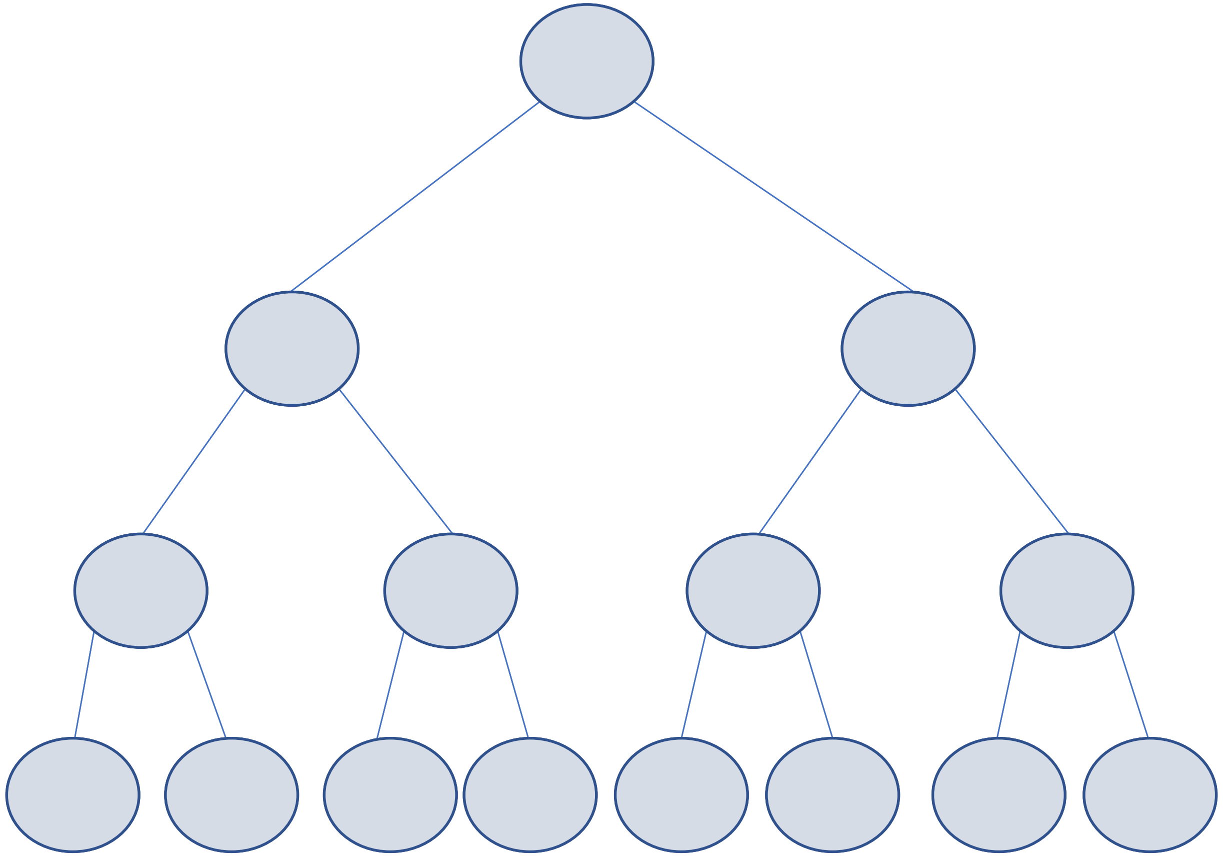


A Tree-based Barrier

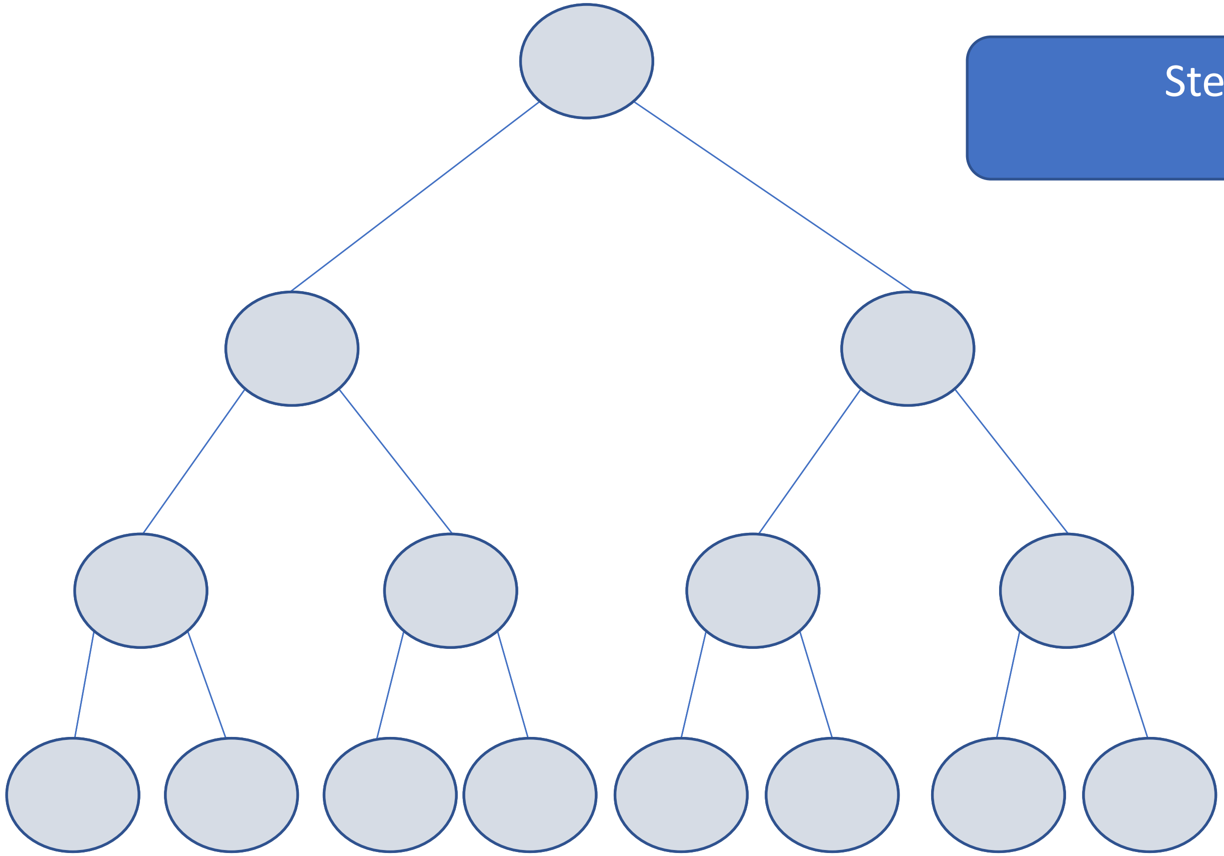
- Threads are organized in a binary tree
- Each node is owned by a predetermined thread
- Each thread waits until its 2 children arrive
    - combines results
    - passes them on to its parent
- Root learns that its 2 children have arrived→tells children they can go
- The signal propagates down the tree until all the threads get the message



A Tree-based Barrier: indexing

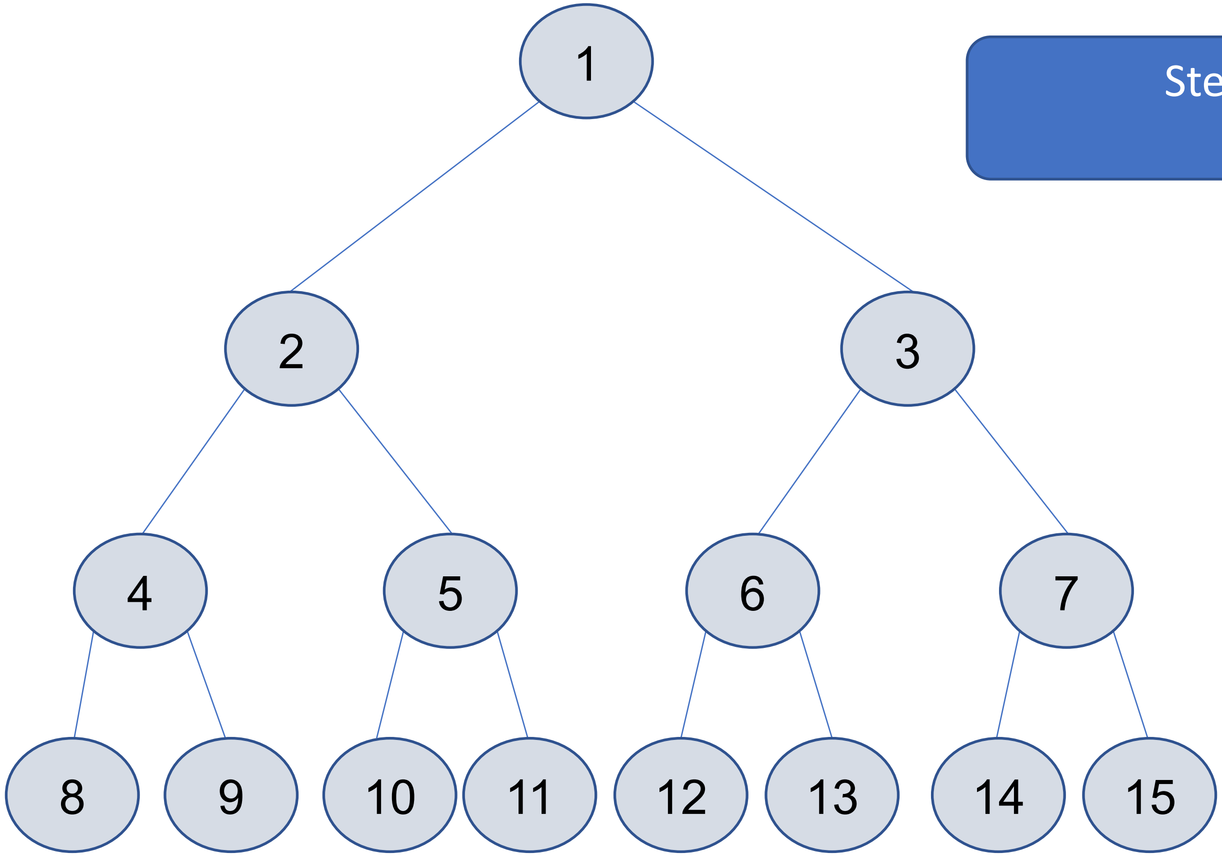


A Tree-based Barrier: indexing



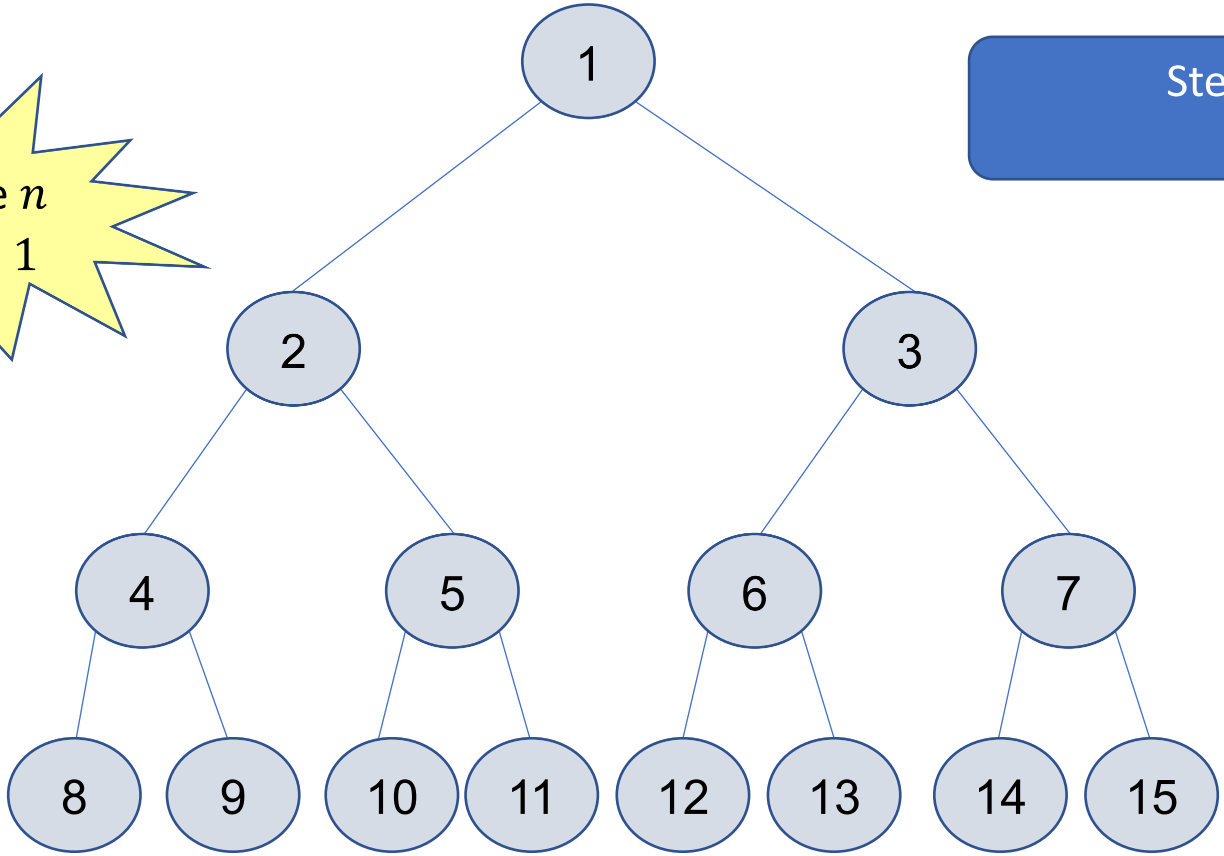
Step 1: label numerically
with traveral

A Tree-based Barrier: indexing



Step 1: label numerically
with traveral

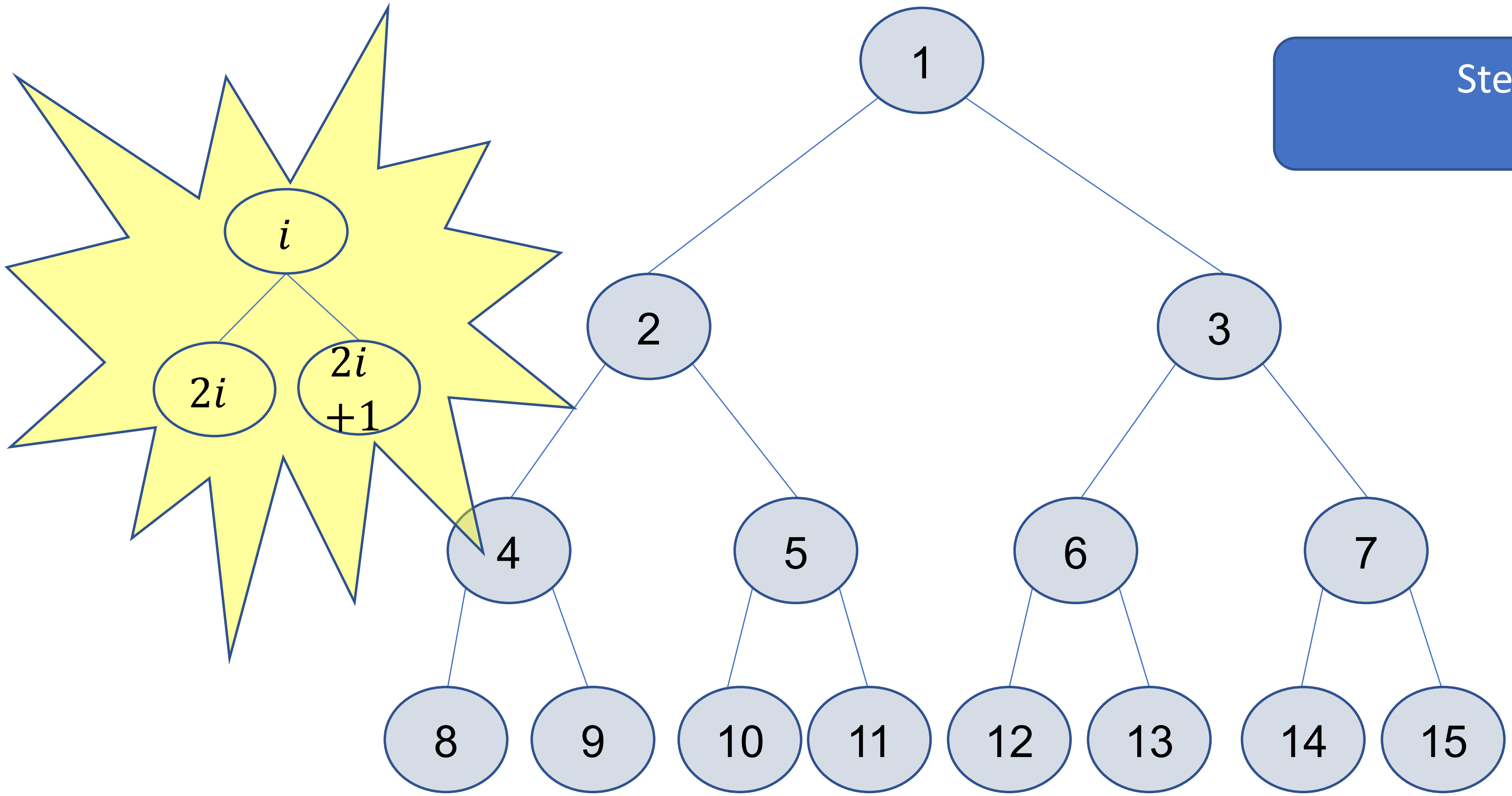
A Tree-based Barrier: indexing



Assume $n = 2^k - 1$

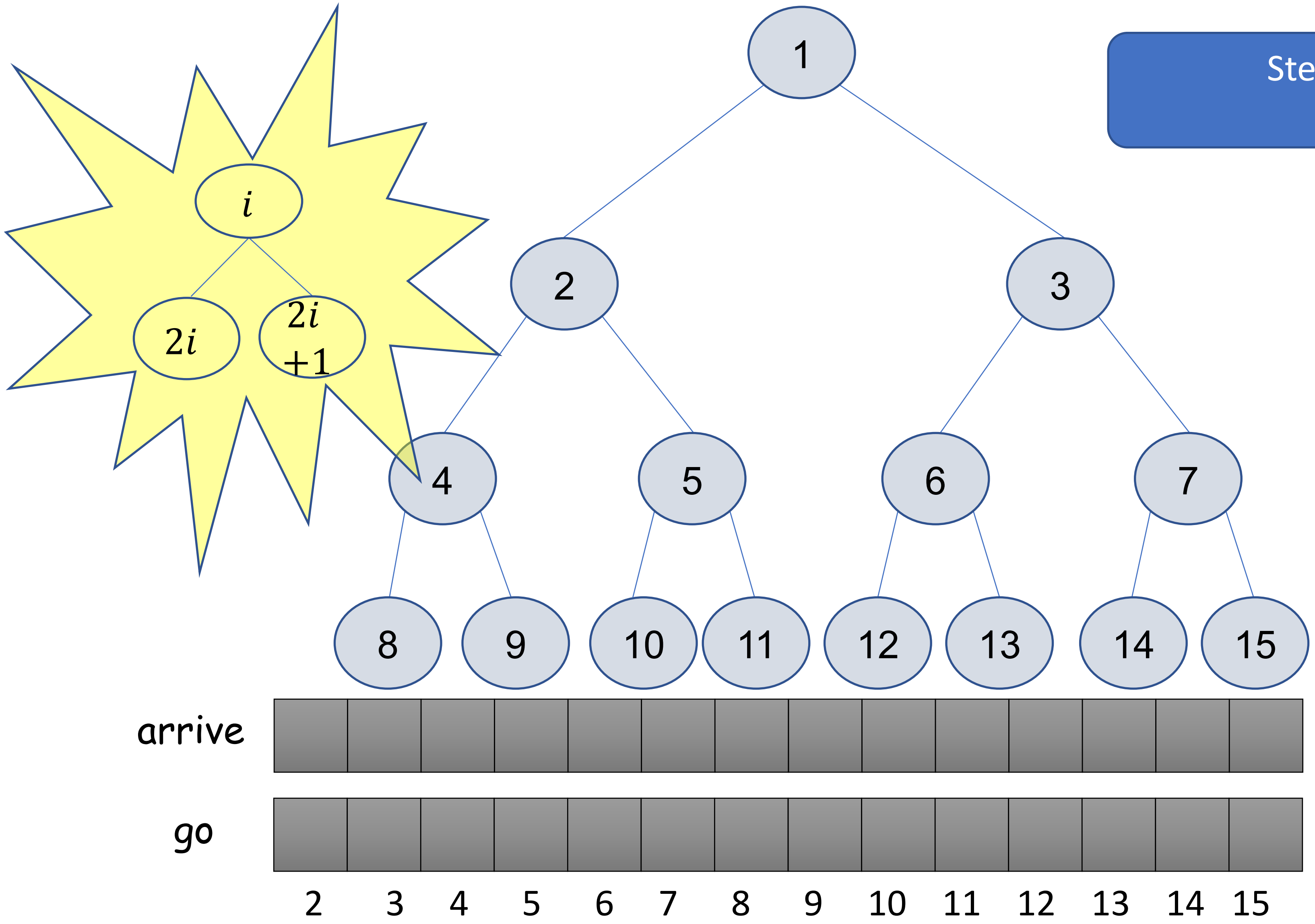
Step 1: label numerically with traveral

A Tree-based Barrier: indexing



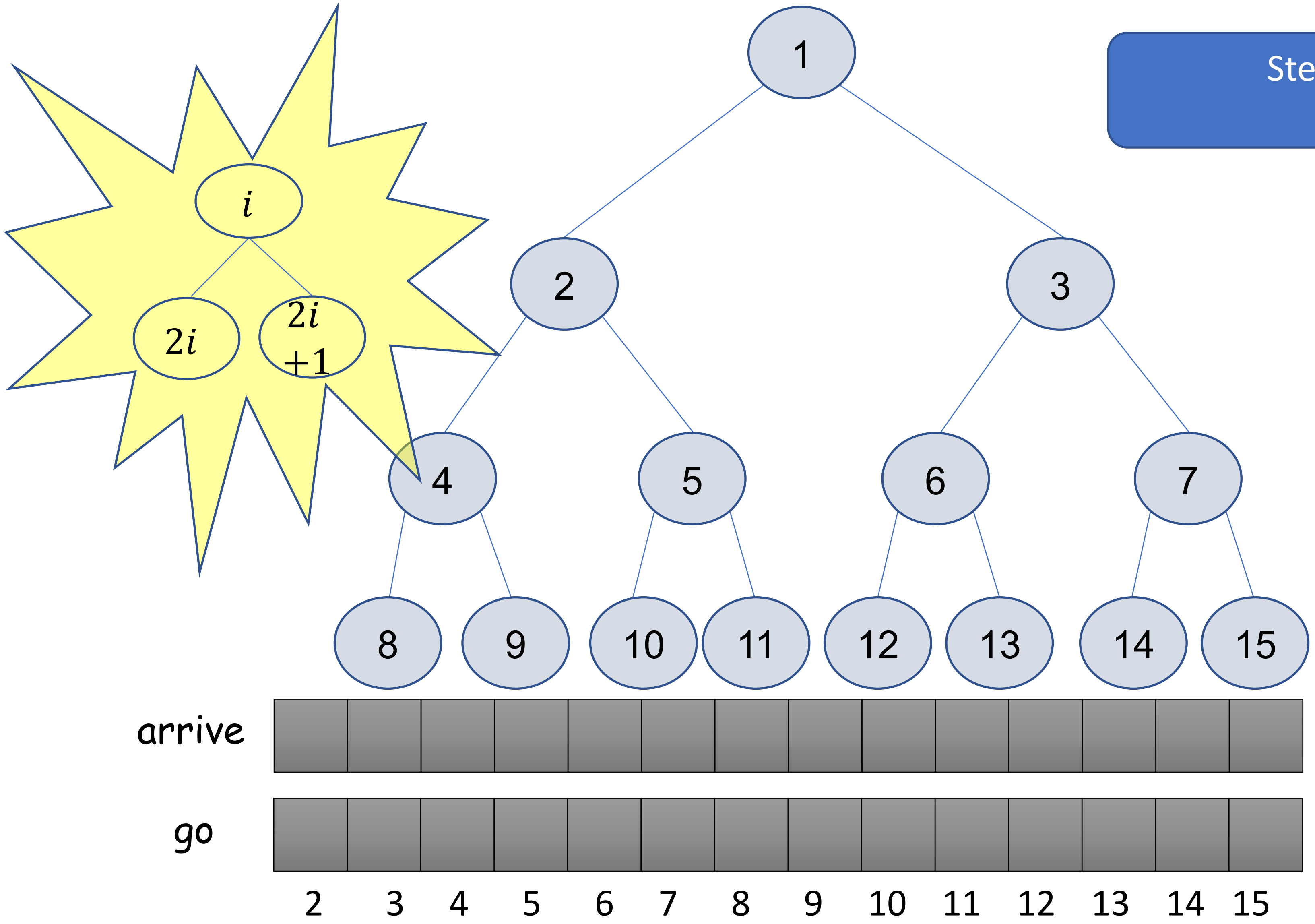
Step 1: label numerically with traveral

A Tree-based Barrier: indexing



Step 1: label numerically
with traveral

A Tree-based Barrier: indexing



Step 1: label numerically with traveral

Indexing starts from 2
Root → 1, doesn’t need wait objects

A Tree-based Barrier

program of thread i

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if $i \le (n-1)/2$ then                       // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier

program of thread i

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

Root

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
```

Internal

```
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
```

Leaf

```
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier

program of thread i

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

Root

Internal

Leaf

```
if i=1 then                                             // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                    // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

Root:
- Wait for arriving children
- Tell children to go

A Tree-based Barrier

program of thread i

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

Root

Internal

Leaf

Root:
- Wait for arriving children
- Tell children to go

Internal:
- Wait for arriving children
- Tell parent about it
- Wait for parent go signal
- Tell children to go

A Tree-based Barrier

program of thread i

shared arrive[2..n]: array of atomic bits, initial values = 0
go[2..n]: array of atomic bits, initial values = 0

Root

```
if i=1 then                                                // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
```

Internal

```
else if i ≤ (n-1)/2 then                                   // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
```

Leaf

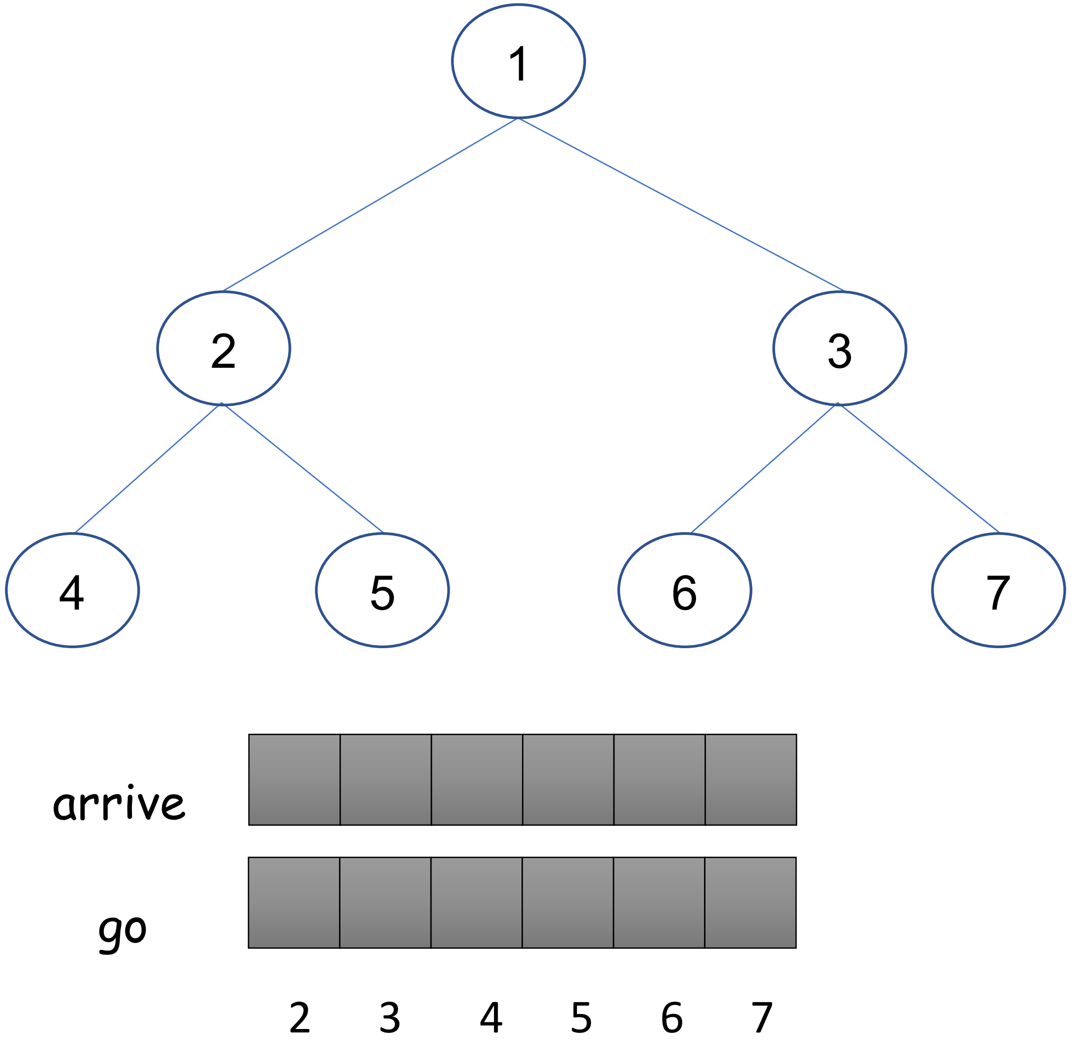
```
else                                                       // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

Root:
- Wait for arriving children
- Tell children to go

Internal:
- Wait for arriving children
- Tell parent about it
- Wait for parent go signal
- Tell children to go

Child:
- arrive
- Wait for parent go signal

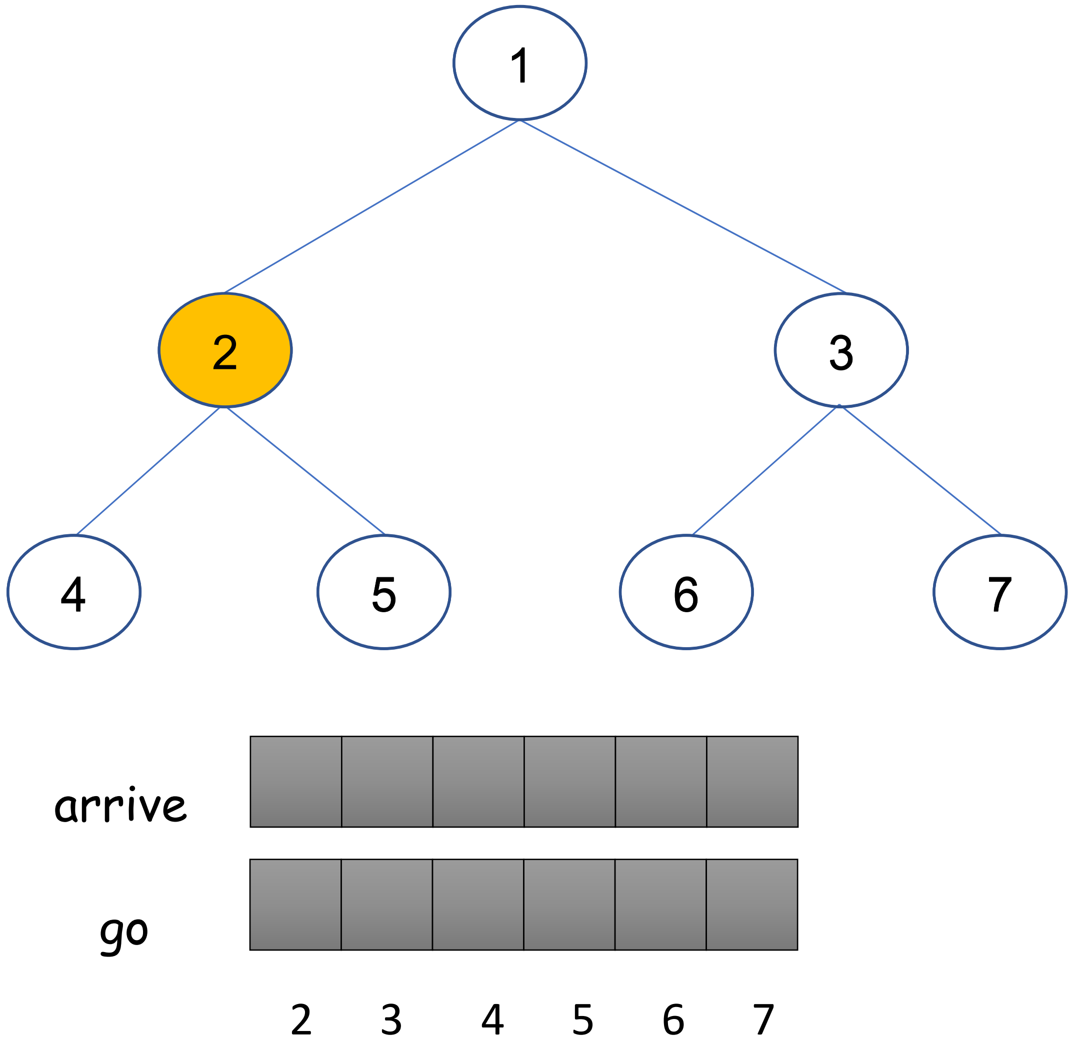
A Tree-based Barrier
Example Run for n=7 threads



```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                             // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                    // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

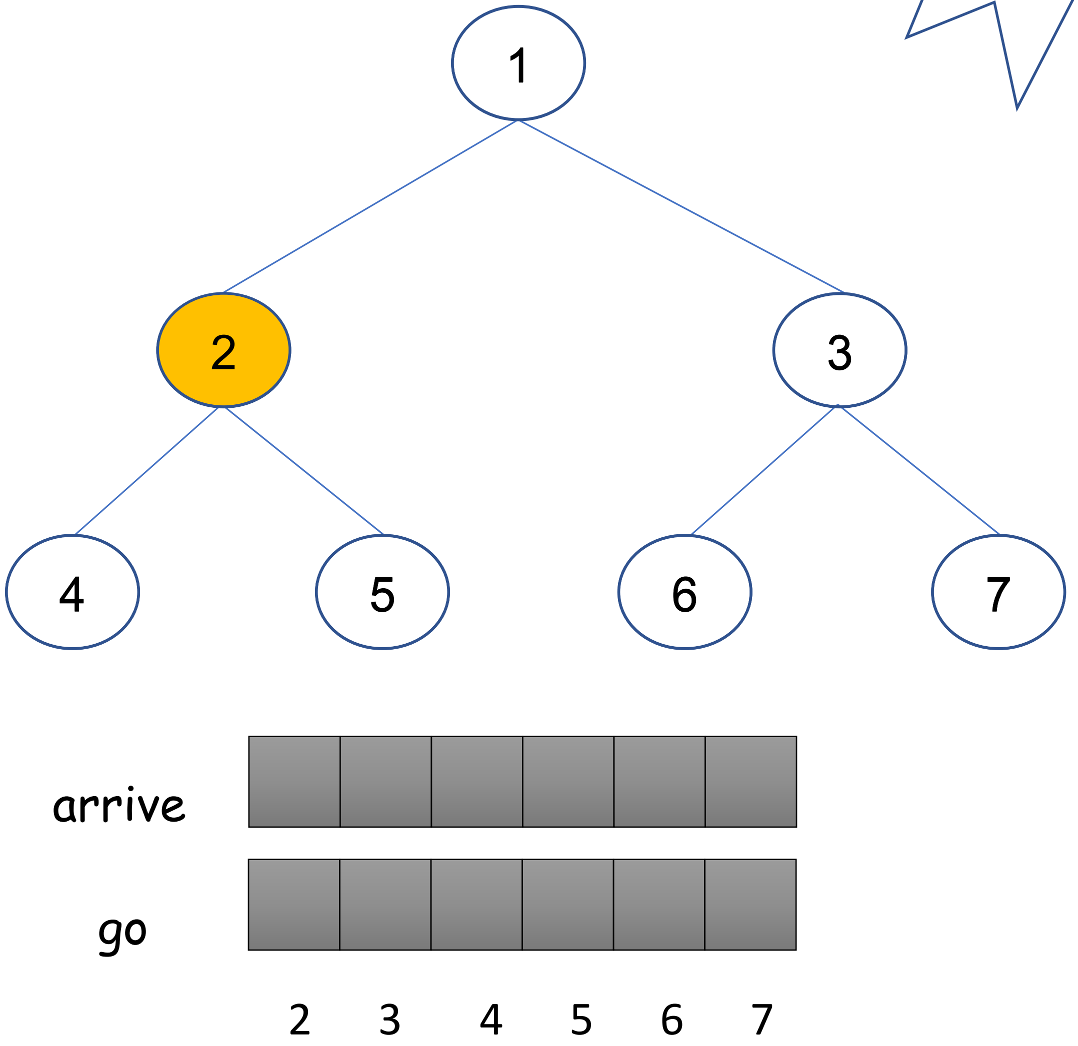


```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

arrive[2]=1 ?



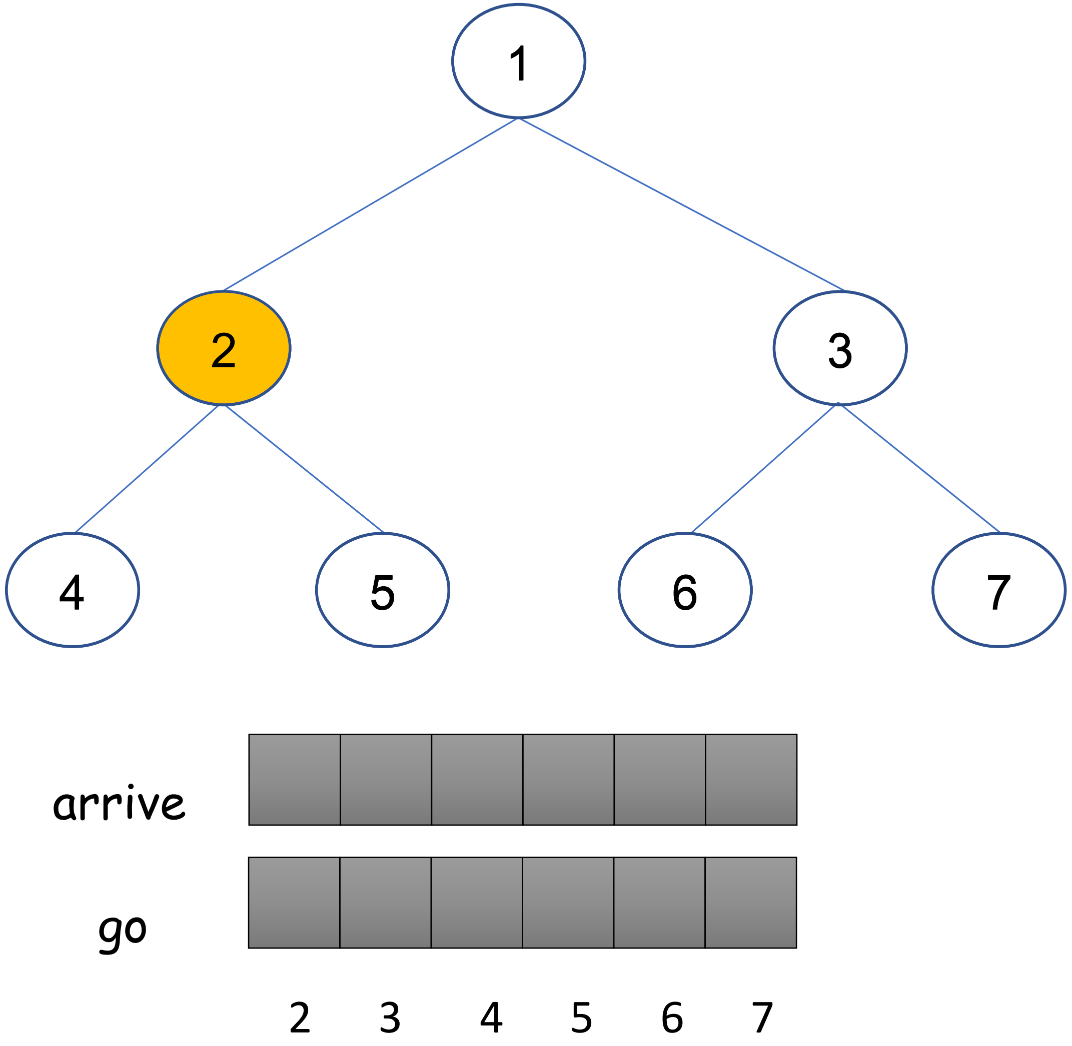
```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

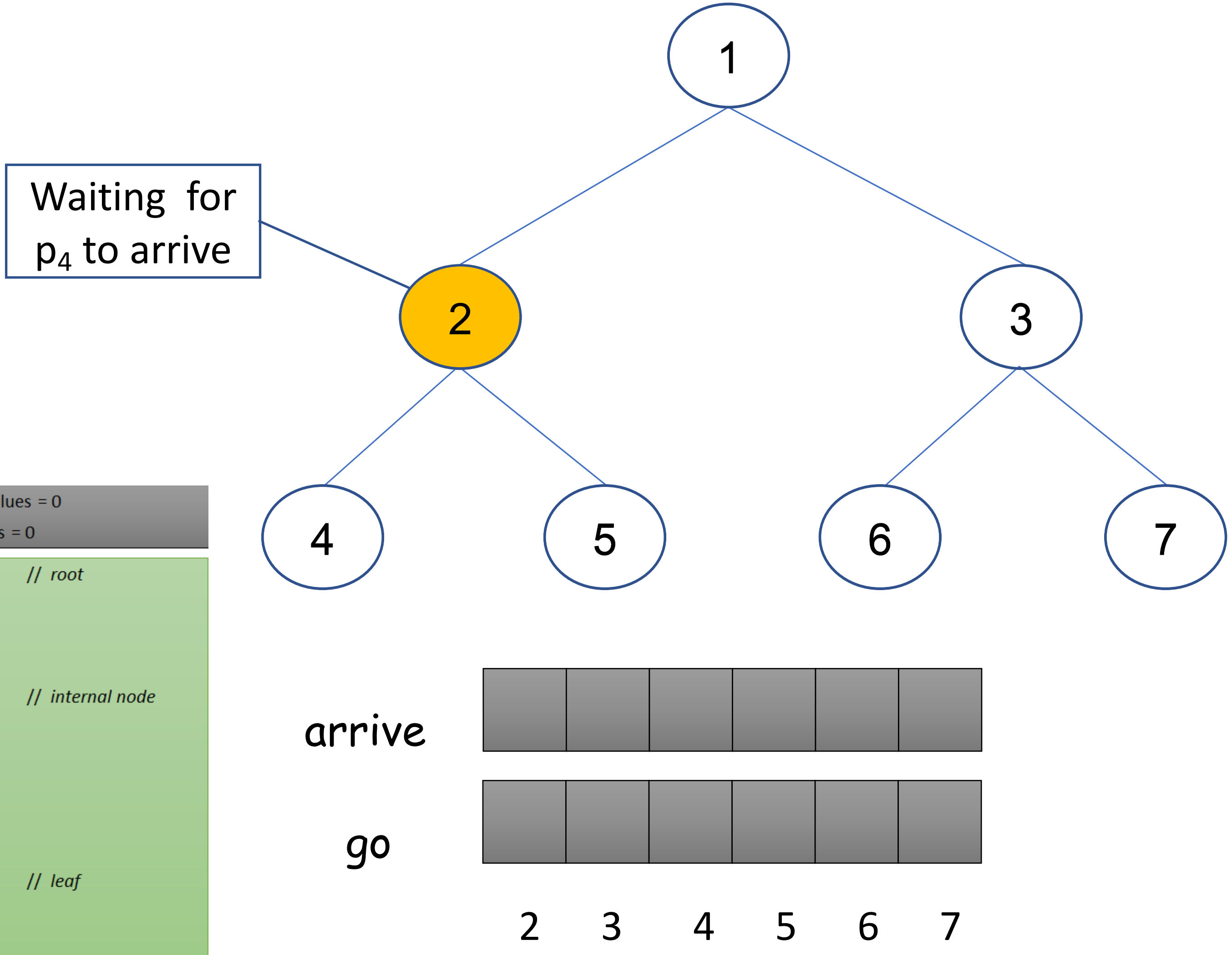
A Tree-based Barrier
Example Run for n=7 threads

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```



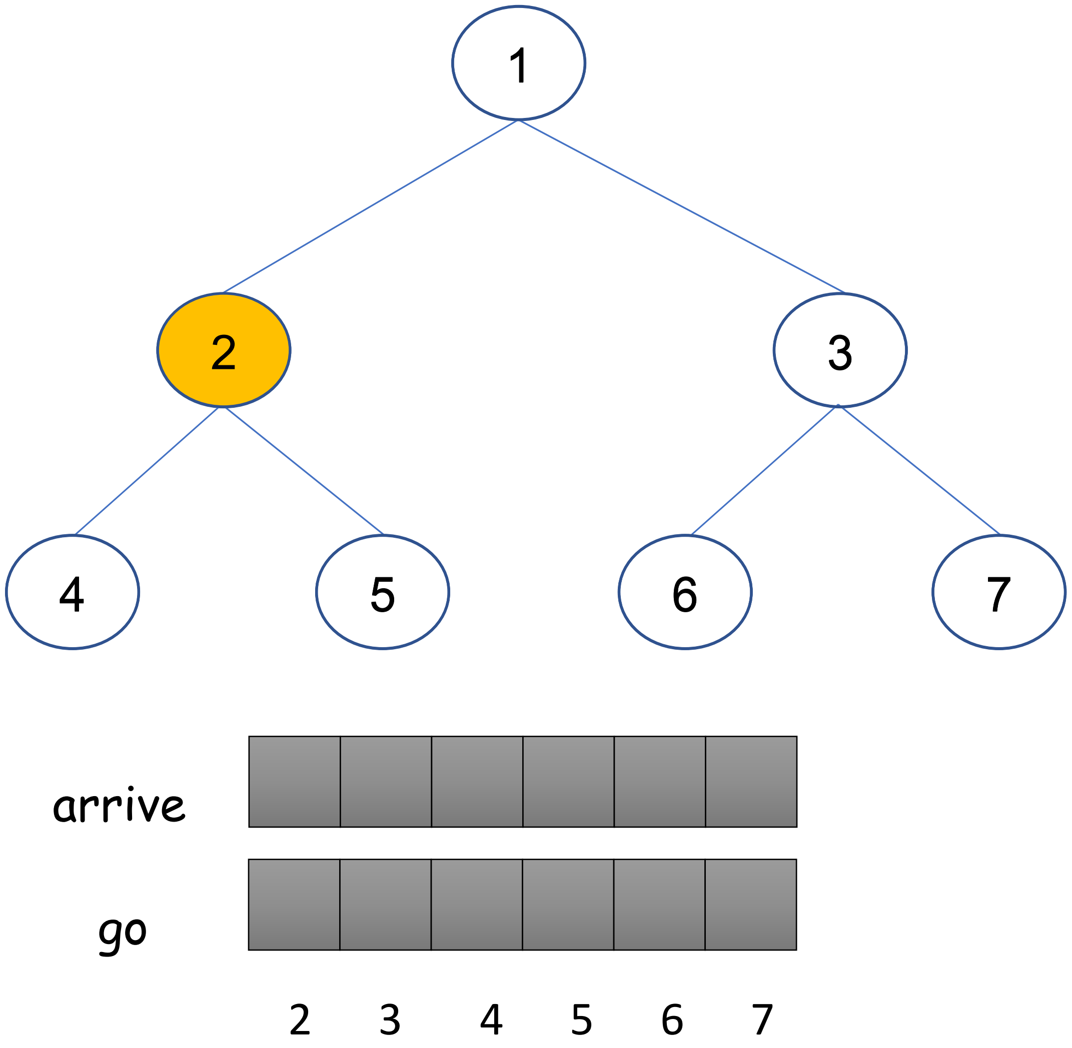
A Tree-based Barrier
Example Run for n=7 threads


Waiting for p_4 to arrive

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

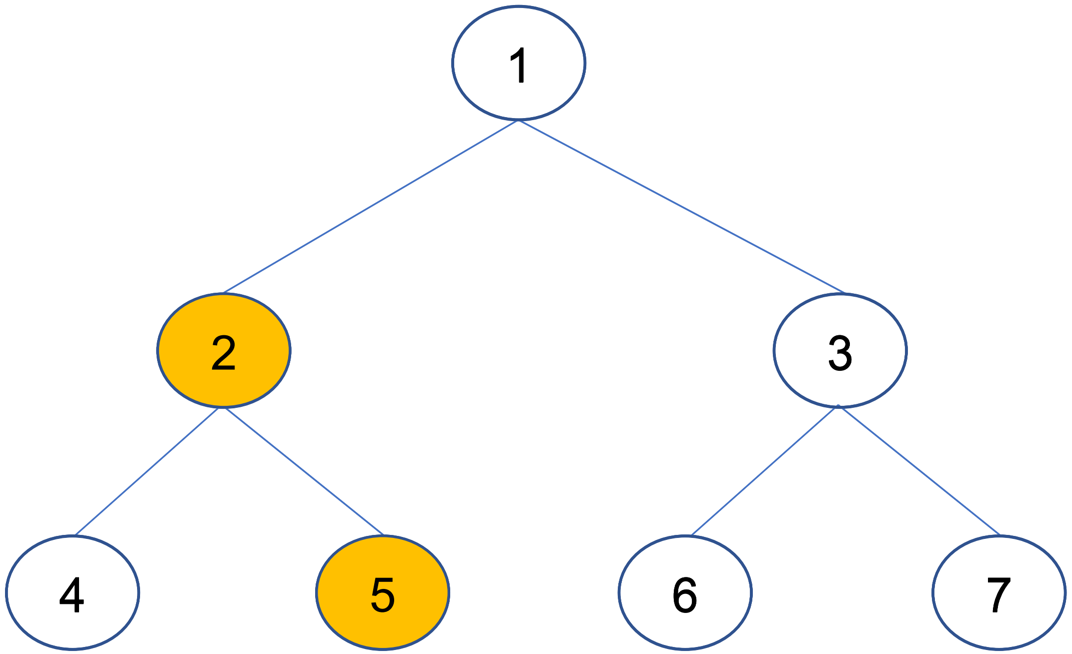
A Tree-based Barrier
Example Run for n=7 threads



```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                      // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                         // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                             // leaf
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

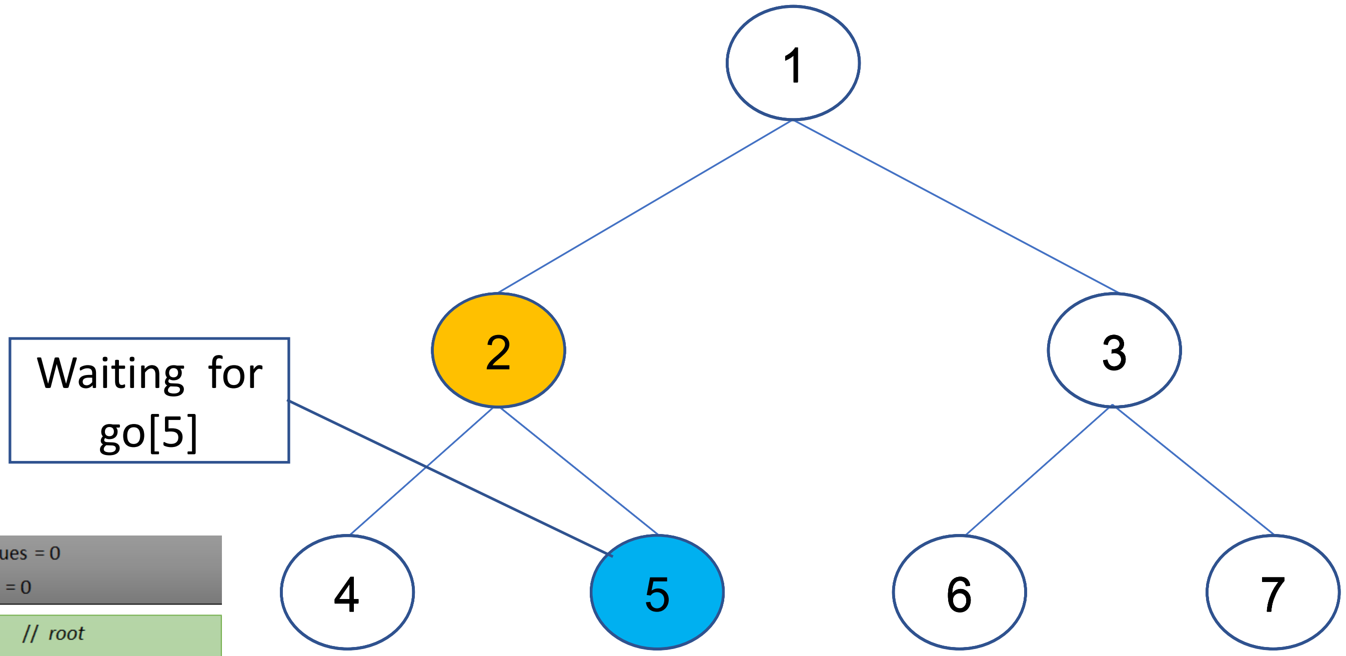


arrive				1		
go						
	2	3	4	5	6	7

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                      // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                         // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                             // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

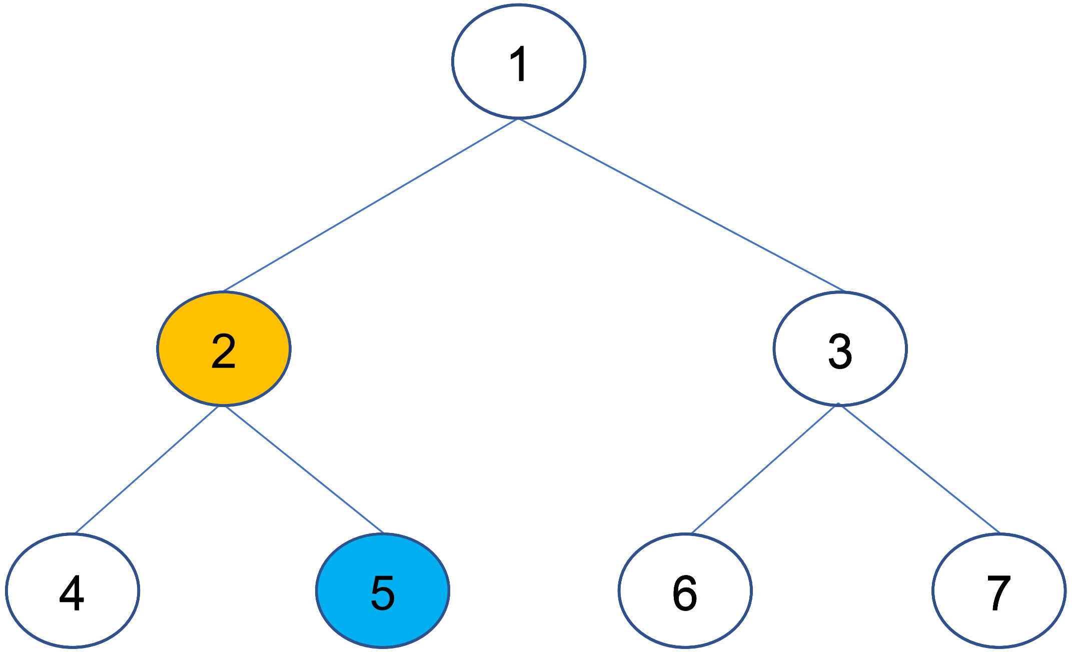


```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive				1		
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

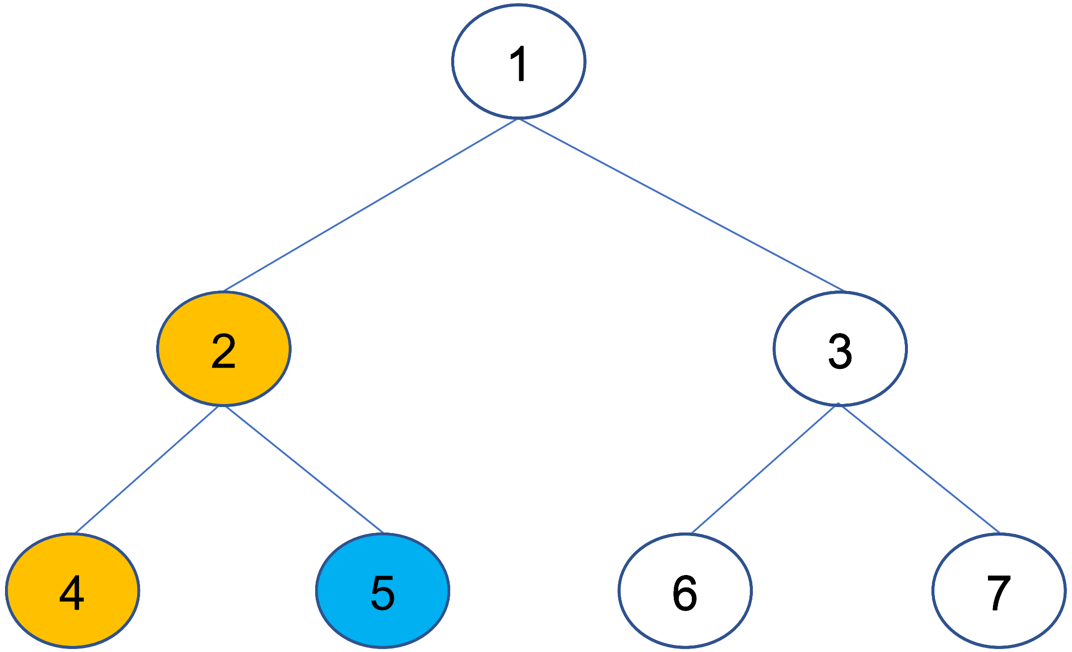


	2	3	4	5	6	7
arrive				1		
go						

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                // leaf
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

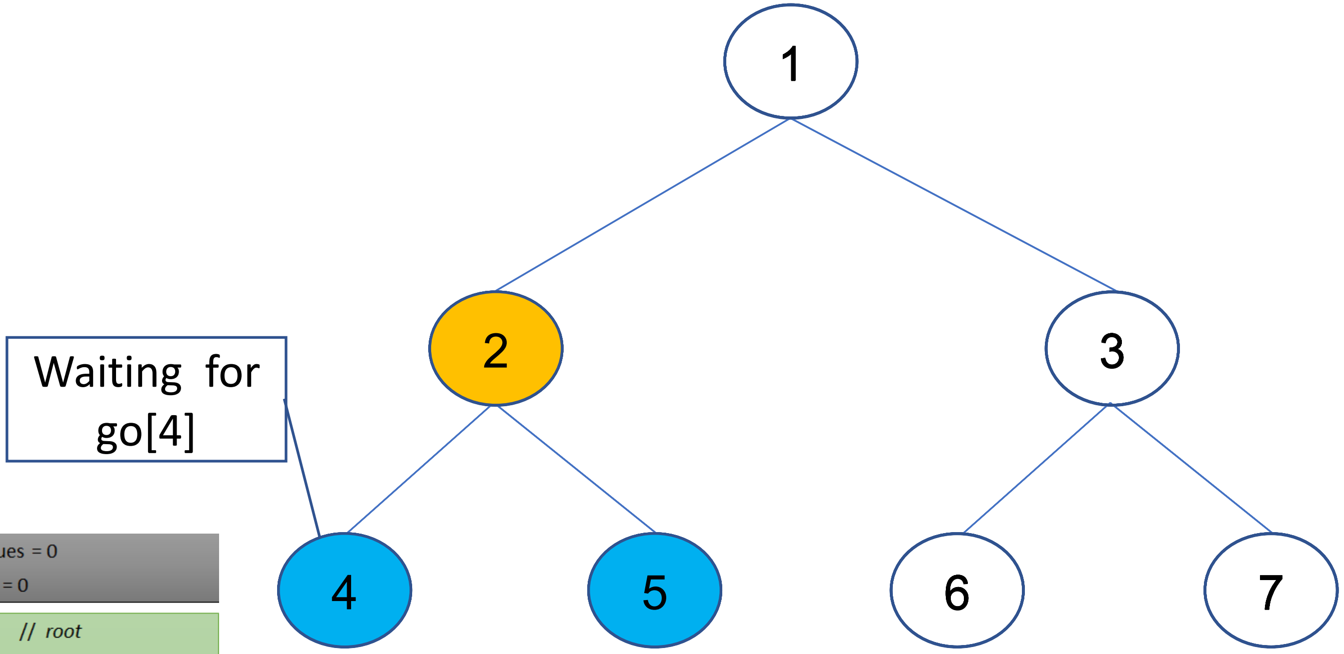


	2	3	4	5	6	7
arrive			1	1		
go						

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                               // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



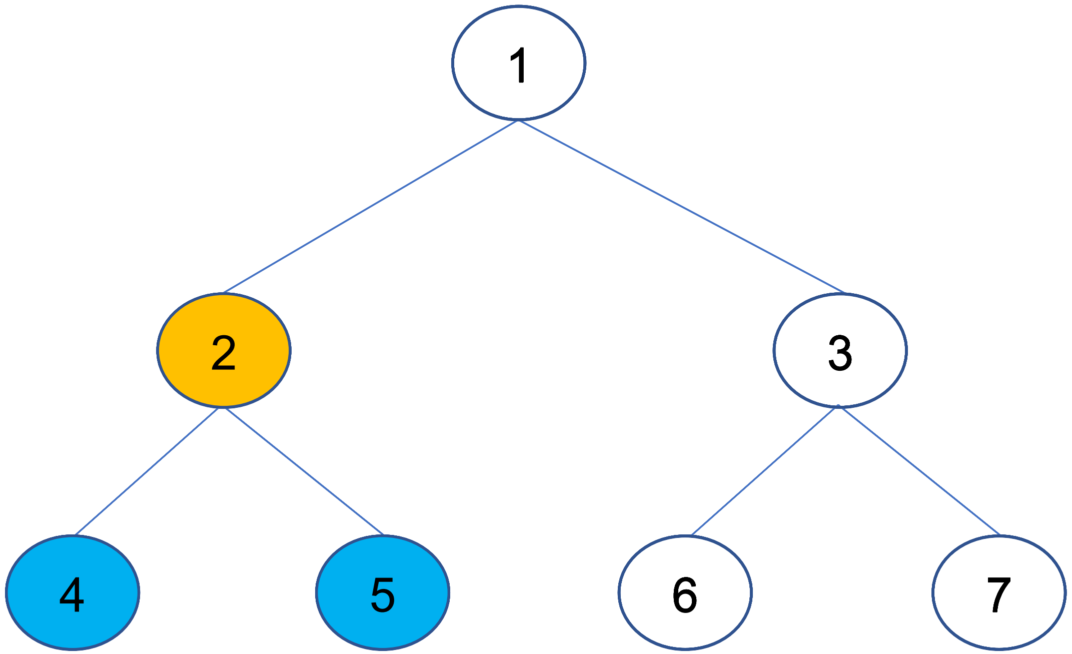
Waiting for go[4]

```
shared  arrive[2..n]: array of atomic bits, initial values = 0
        go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive			1	1		
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



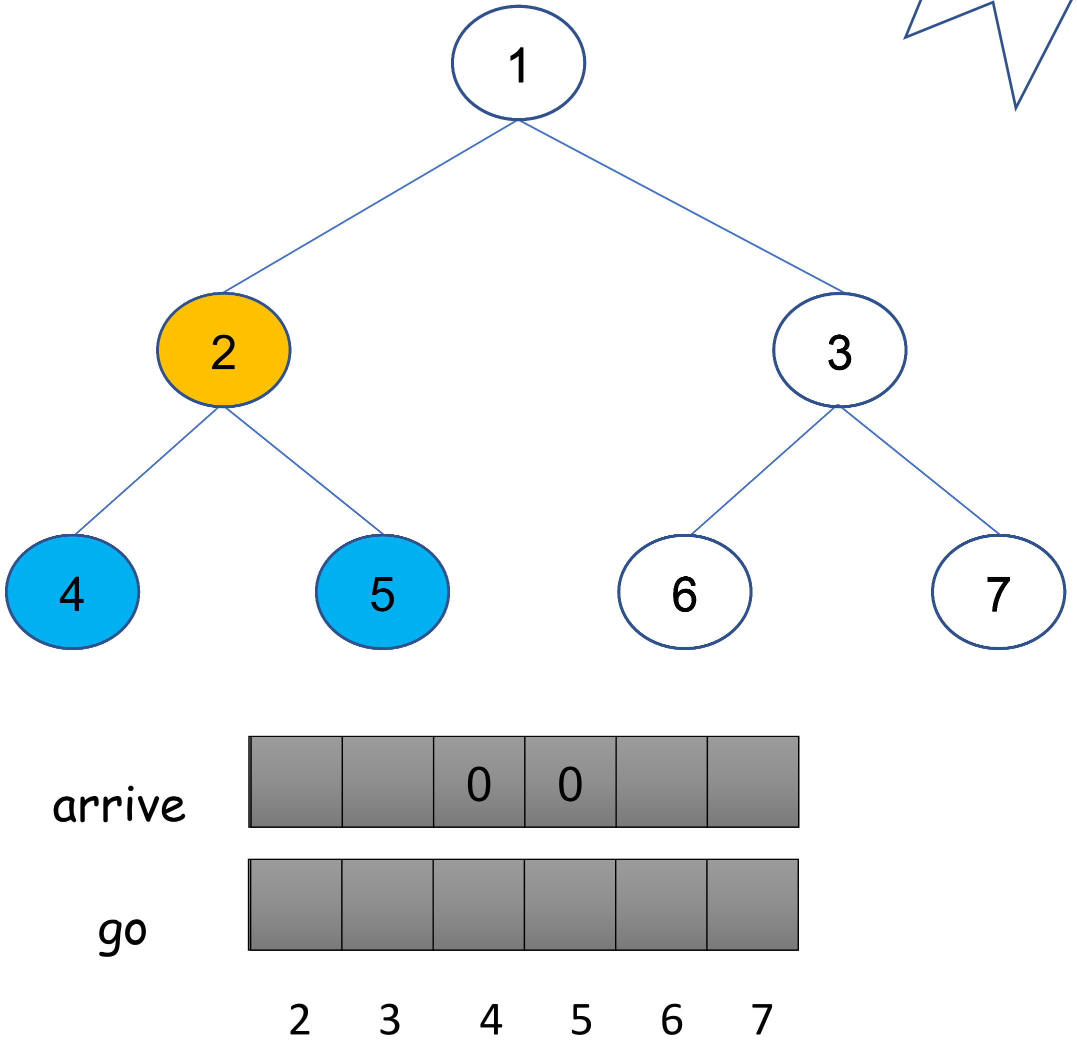
	2	3	4	5	6	7
arrive			1	1		
go						

```
shared      arrive[2..n]:  array of atomic bits, initial values = 0
            go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                           // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                              // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                  // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

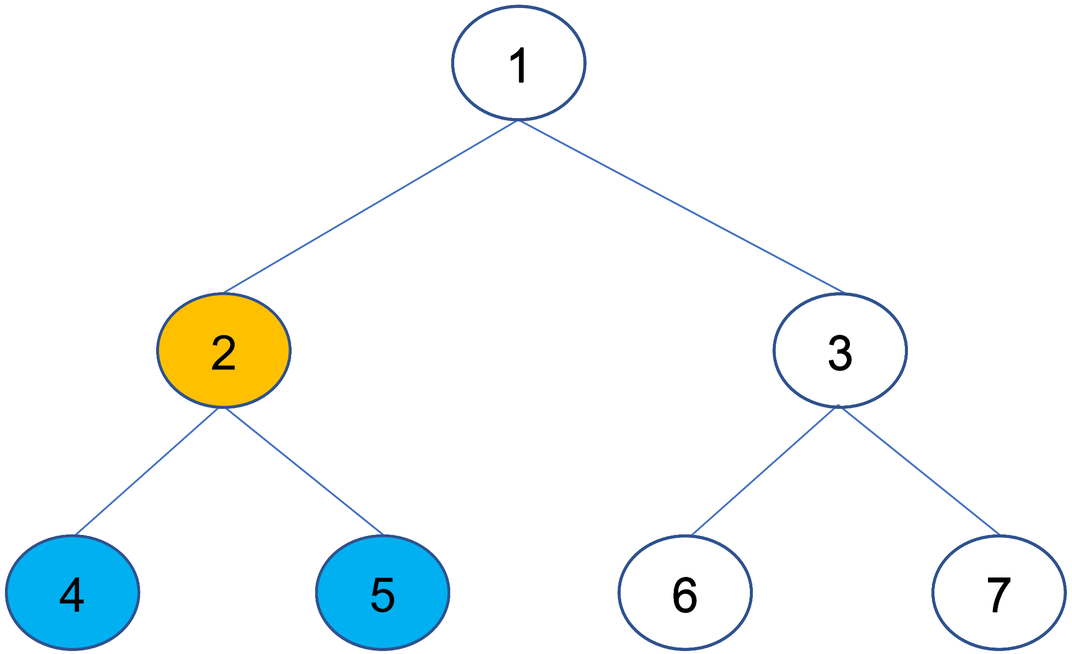
P_2 zeros arrive[4,5]



```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                    // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                       // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                           // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



arrive			0	0		
go						
	2	3	4	5	6	7

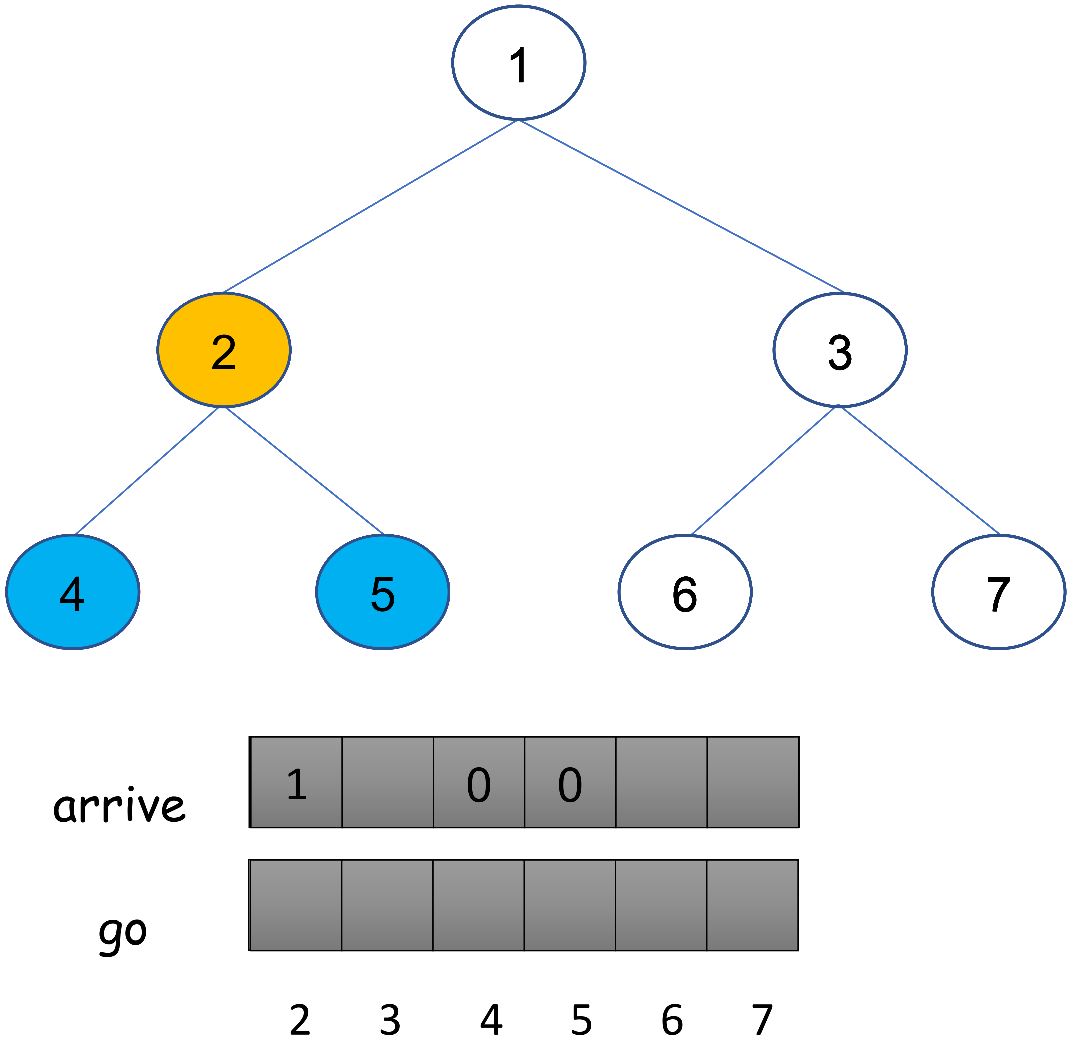
```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i]  := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i]  := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

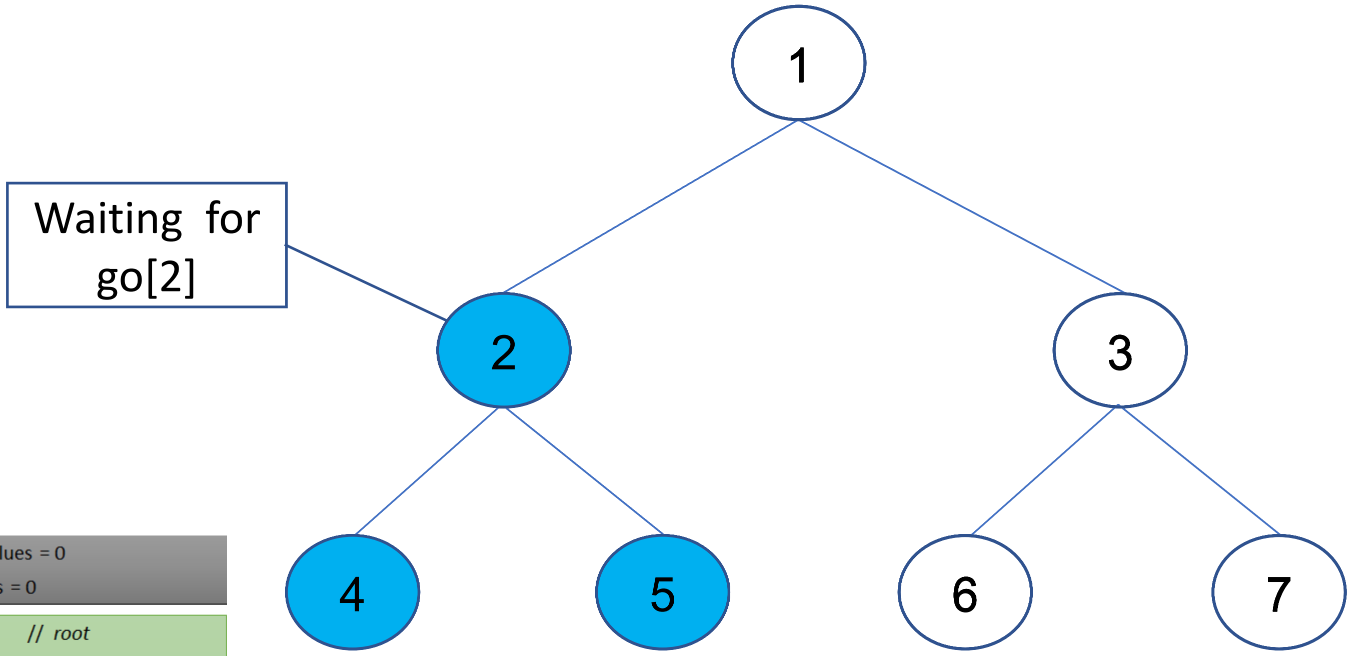
```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```



arrive	1		0	0		
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

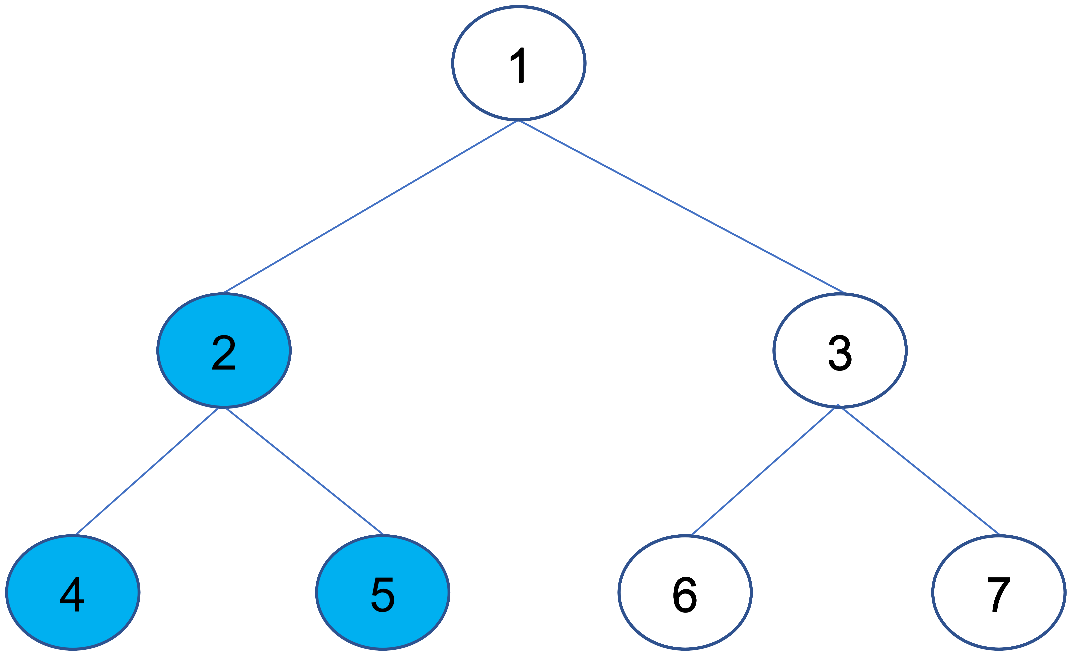


```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                               // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	1		0	0		
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

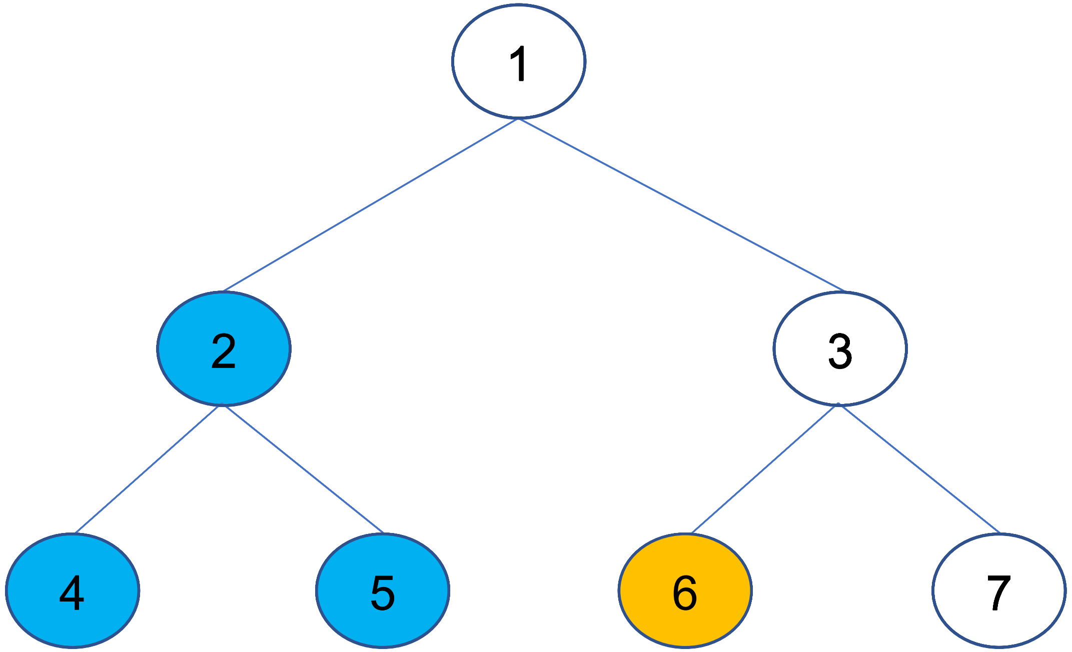


arrive	1		0	0		
go						
	2	3	4	5	6	7

```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                  // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                     // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                         // leaf
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

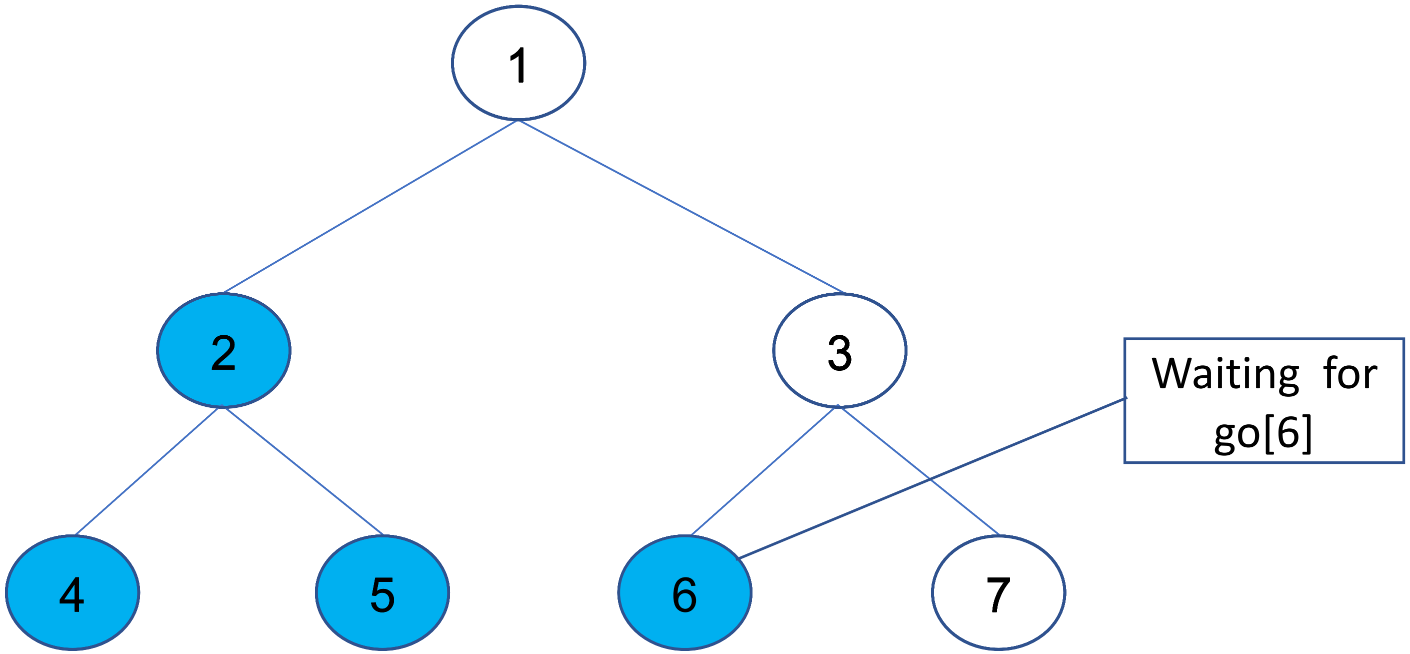


arrive	1		0	0	1	
go						
	2	3	4	5	6	7

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



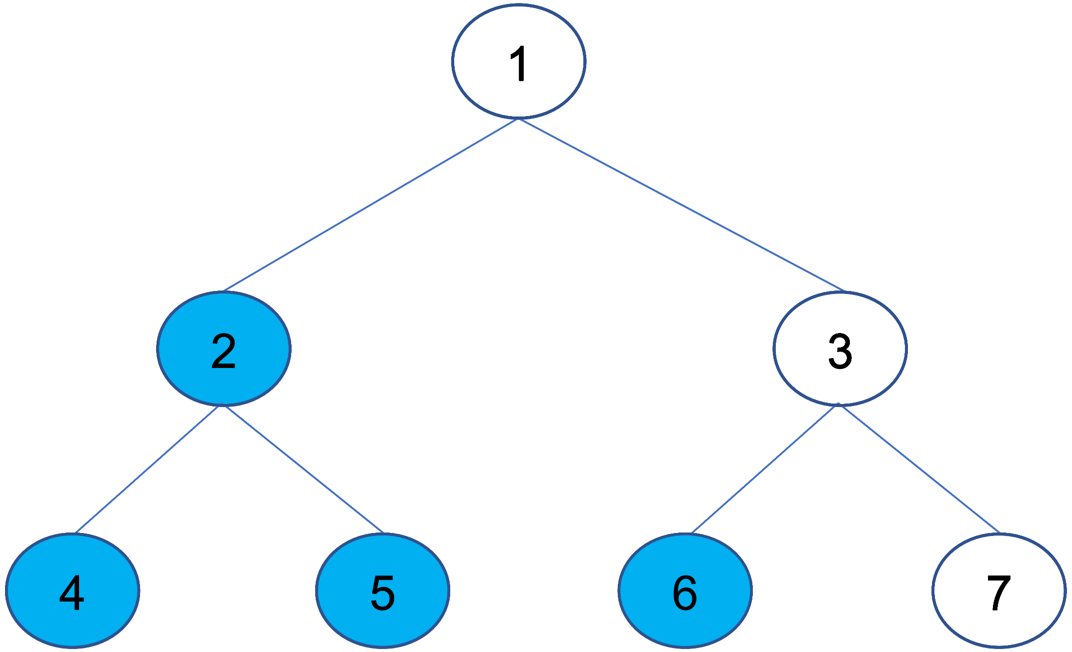
Waiting for go[6]

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                              // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                 // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                     // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	1		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

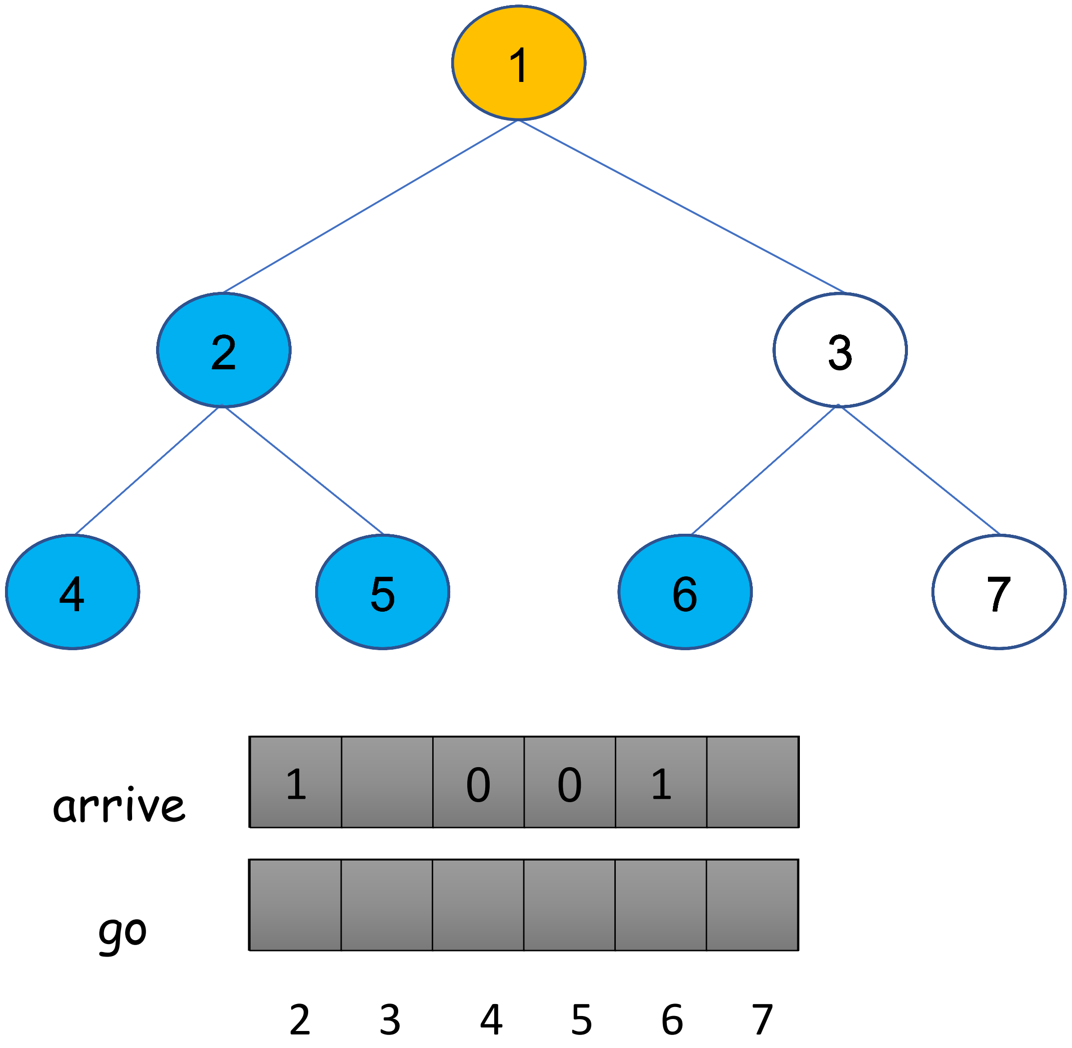


```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2] := 0
        await(arrive[3]  = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

arrive	1		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



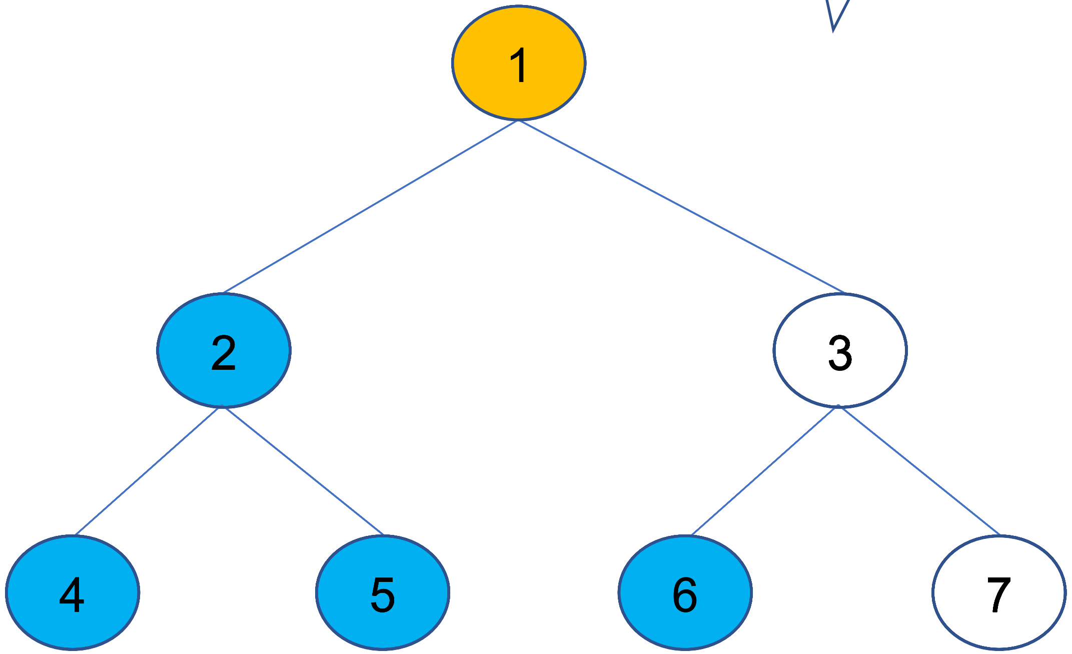
	2	3	4	5	6	7
arrive	1		0	0	1	
go						

```
shared      arrive[2..n]: array of atomic bits, initial values = 0
            go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                              // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                 // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                     // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

`Arrive[2]=1`
`?`

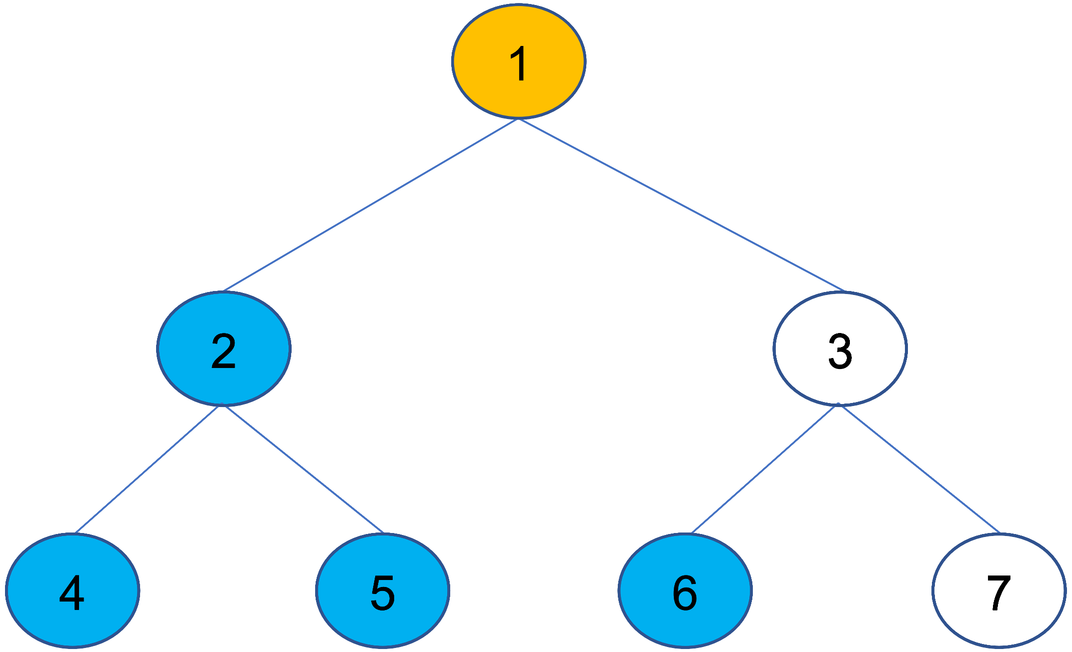


arrive	1		0	0	1	
go						
	2	3	4	5	6	7

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

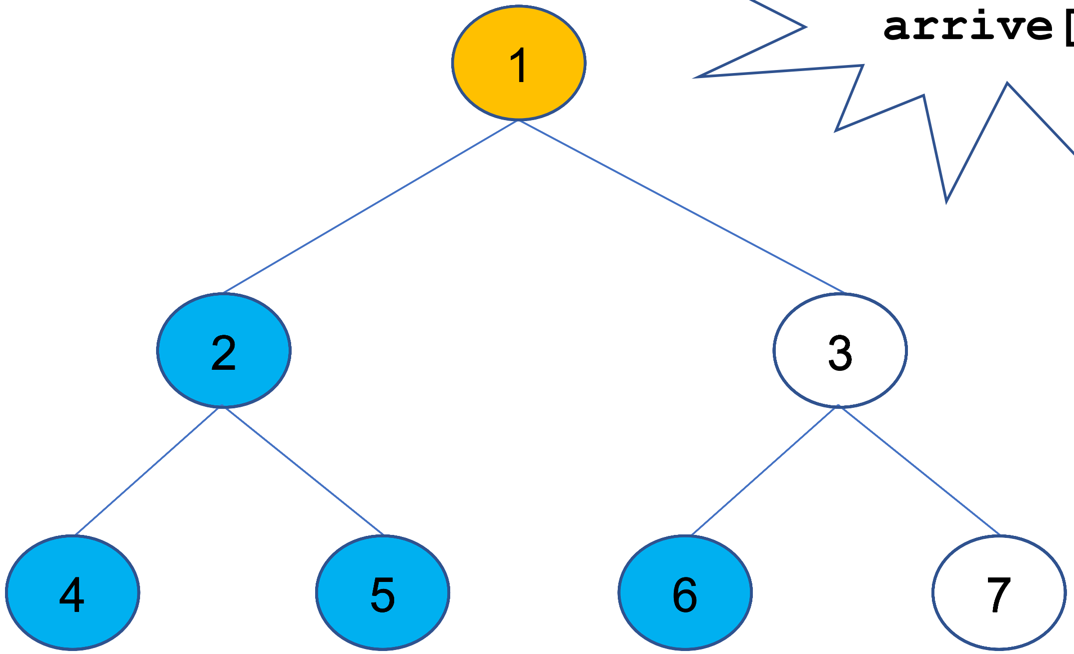


	2	3	4	5	6	7
arrive	1		0	0	1	
go						

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                    // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                       // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                           // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



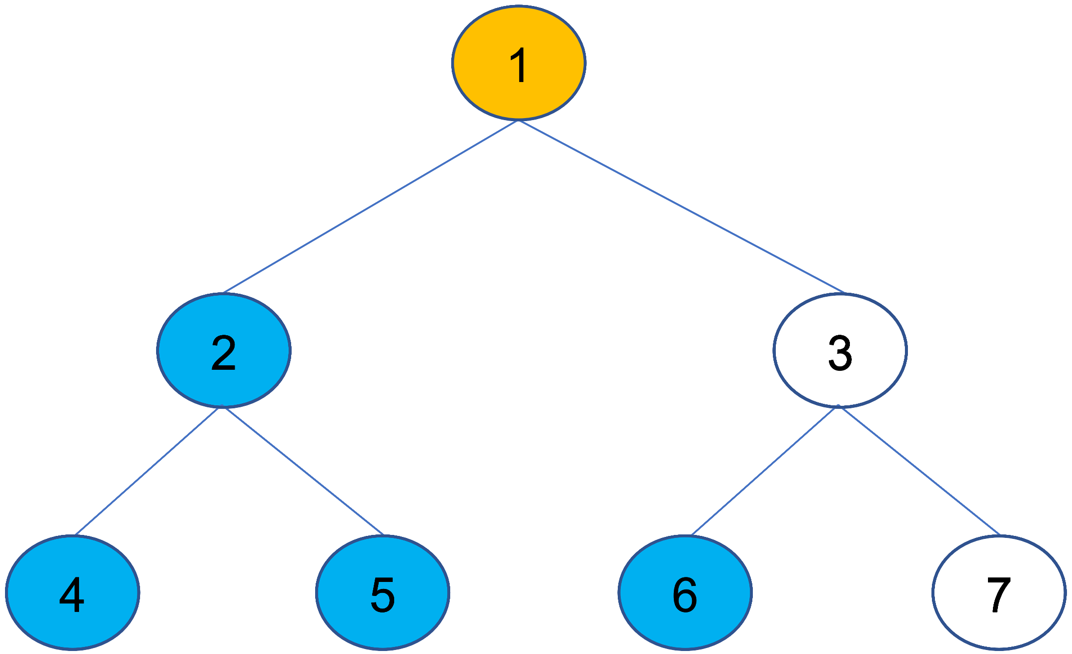
P_1 zeros arrive[2]

	2	3	4	5	6	7
arrive	0		0	0	1	
go						

```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i]  := 1
    await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

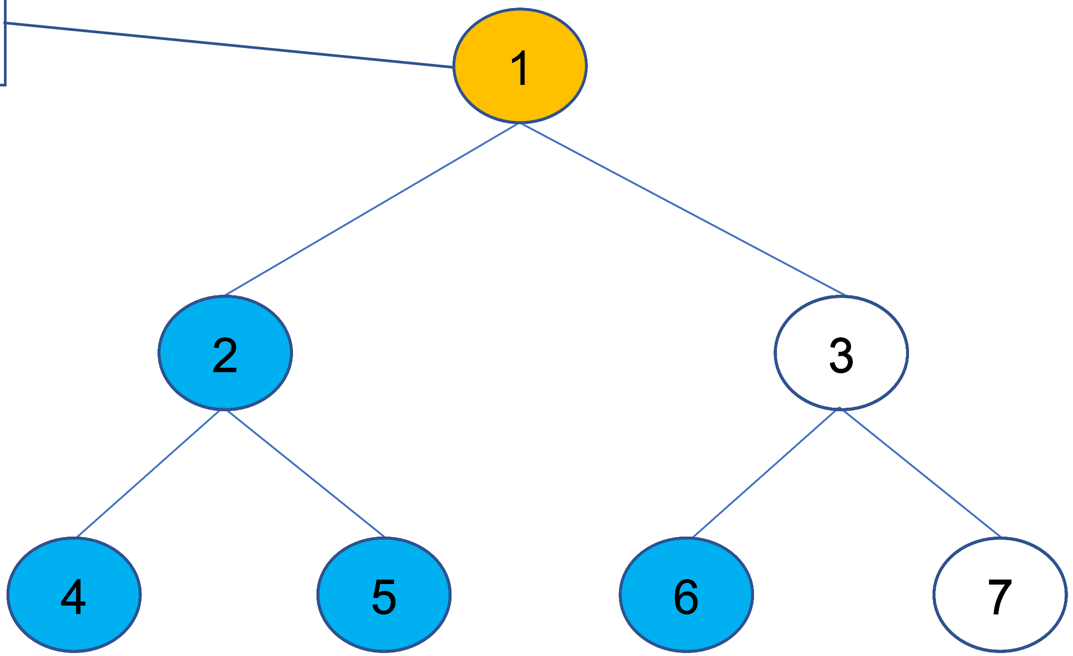


arrive	0		0	0	1	
go						
	2	3	4	5	6	7

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



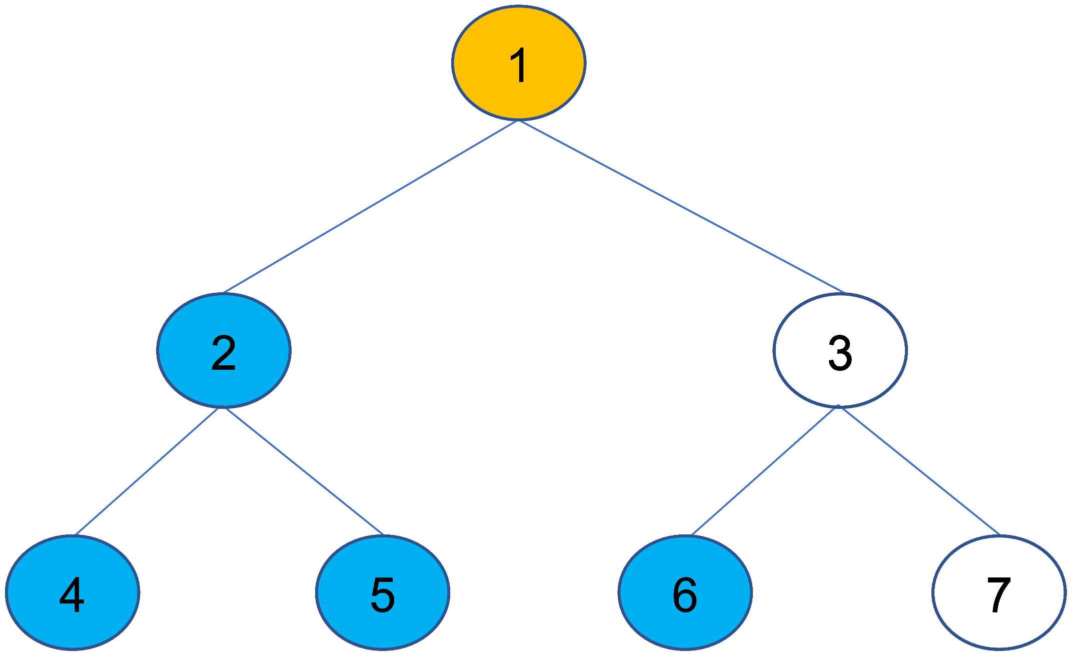
Waiting for p_3 to arrive

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

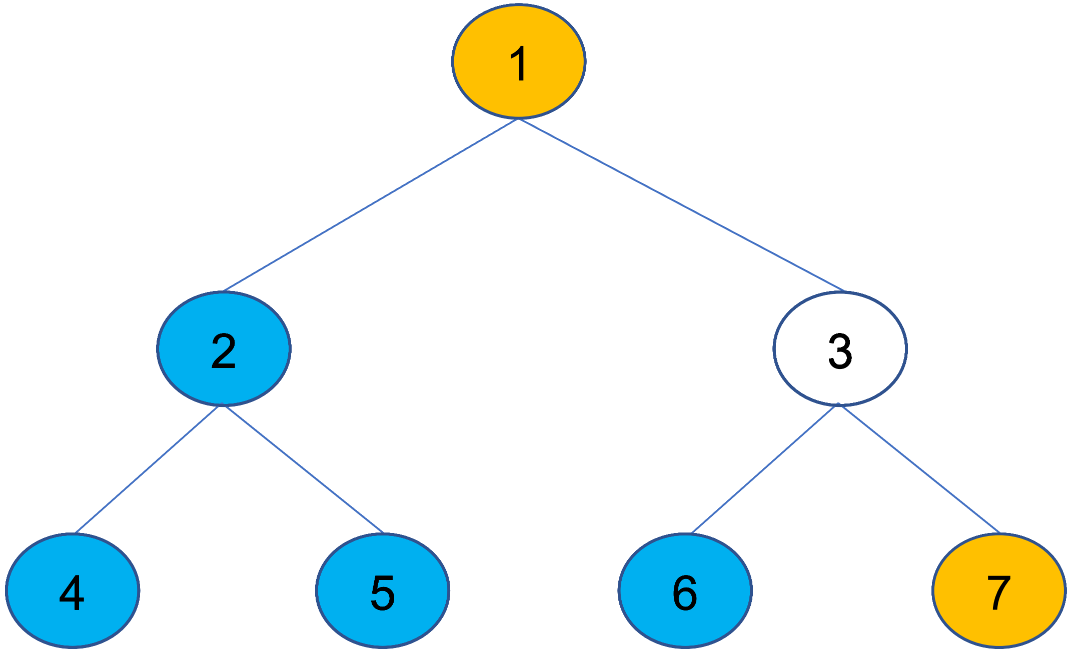


```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

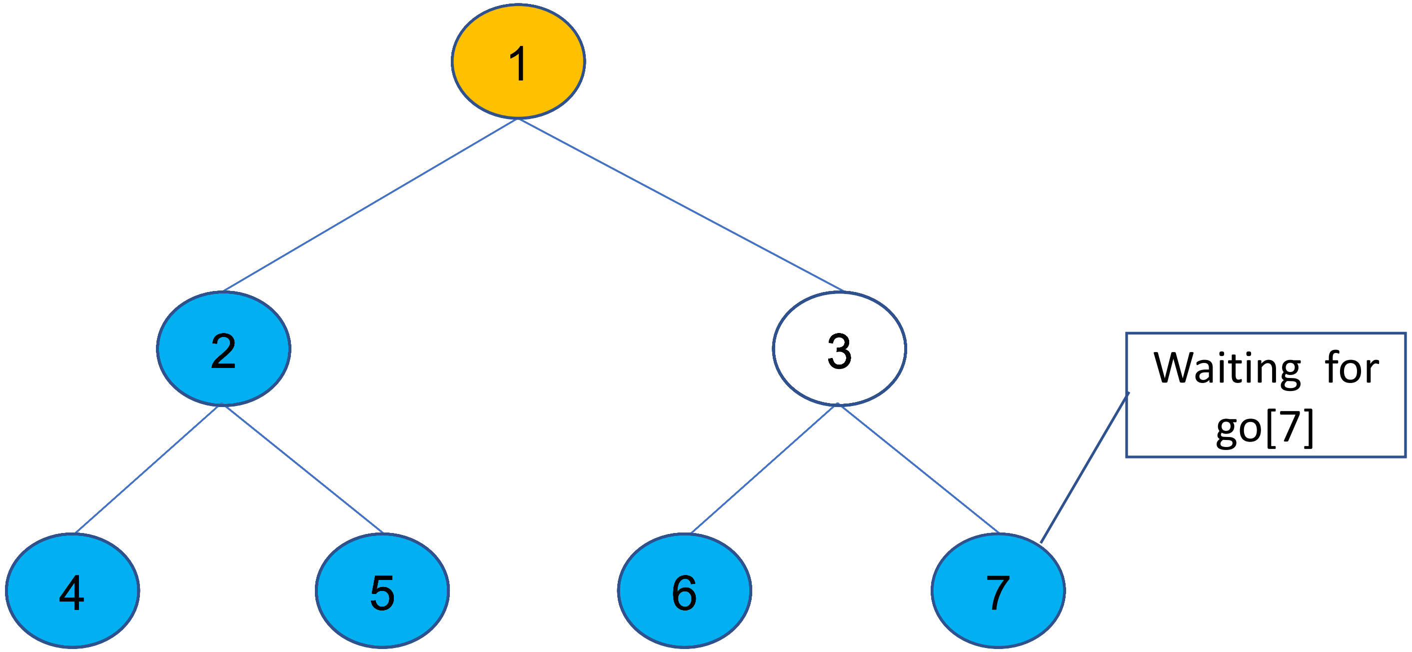


arrive	0		0	0	1	1
go						
	2	3	4	5	6	7

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



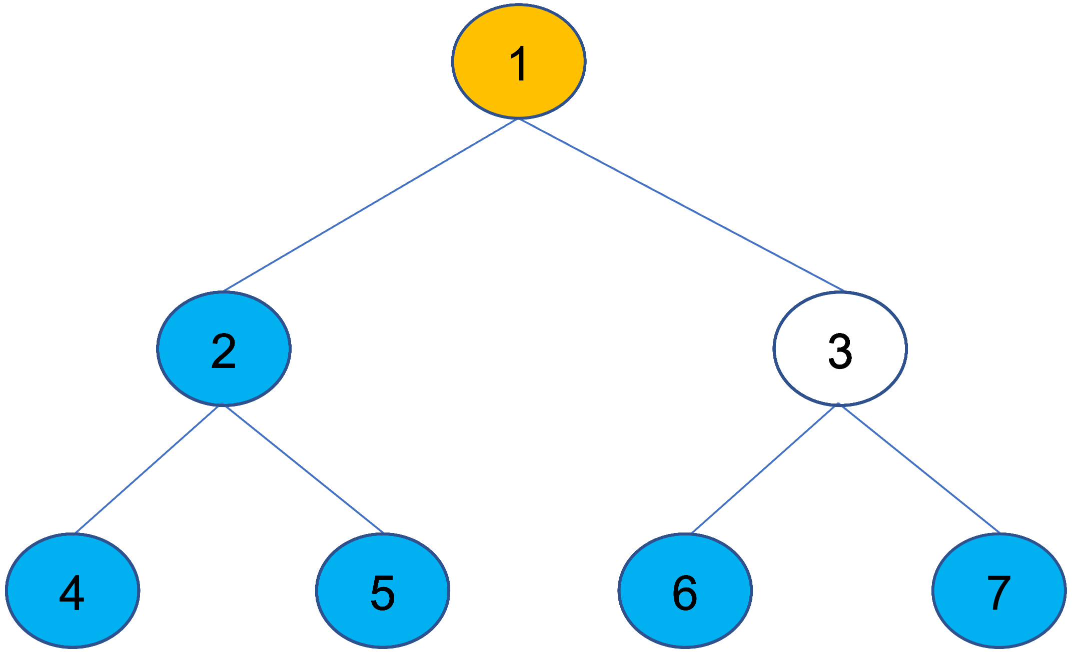
Waiting for go[7]

arrive	0		0	0	1	1
go						
	2	3	4	5	6	7

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

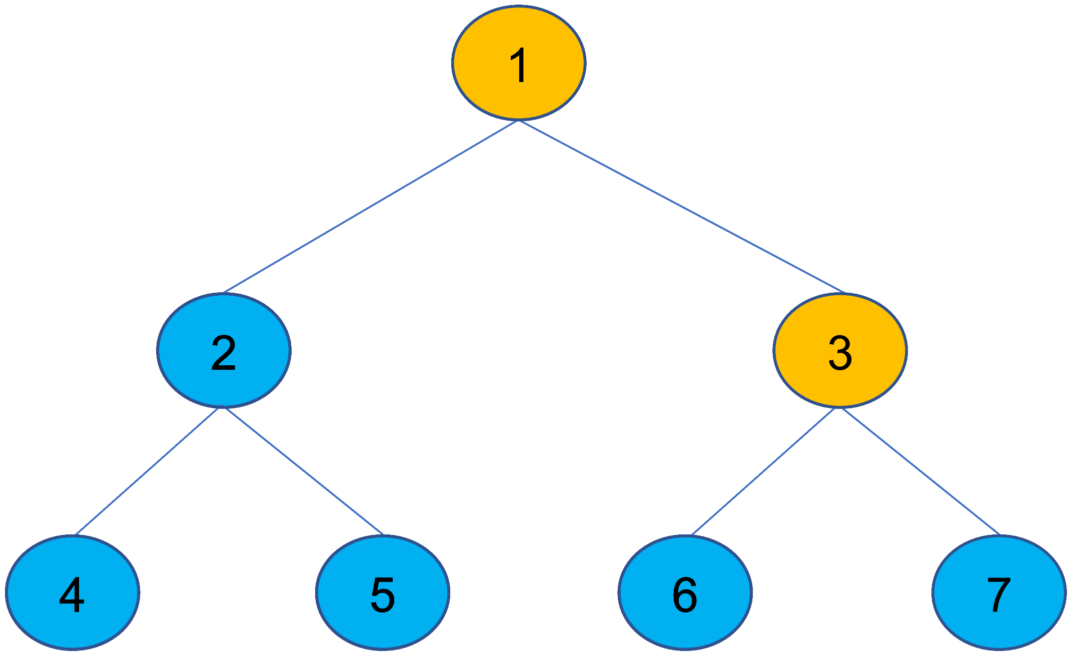


	2	3	4	5	6	7
arrive	0		0	0	1	1
go						

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
        await(arrive[2]  = 1); arrive[2] := 0
        await(arrive[3]  = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                               // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



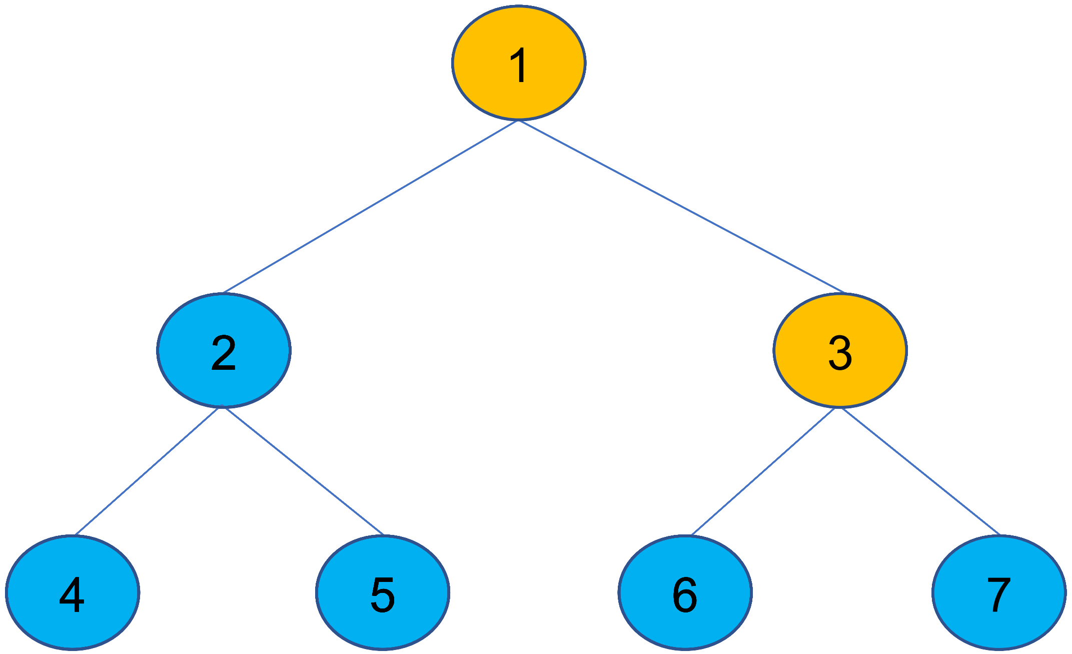
arrive	0		0	0	1	1
go						
	2	3	4	5	6	7

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

P_3 zeros arrive[6,7]

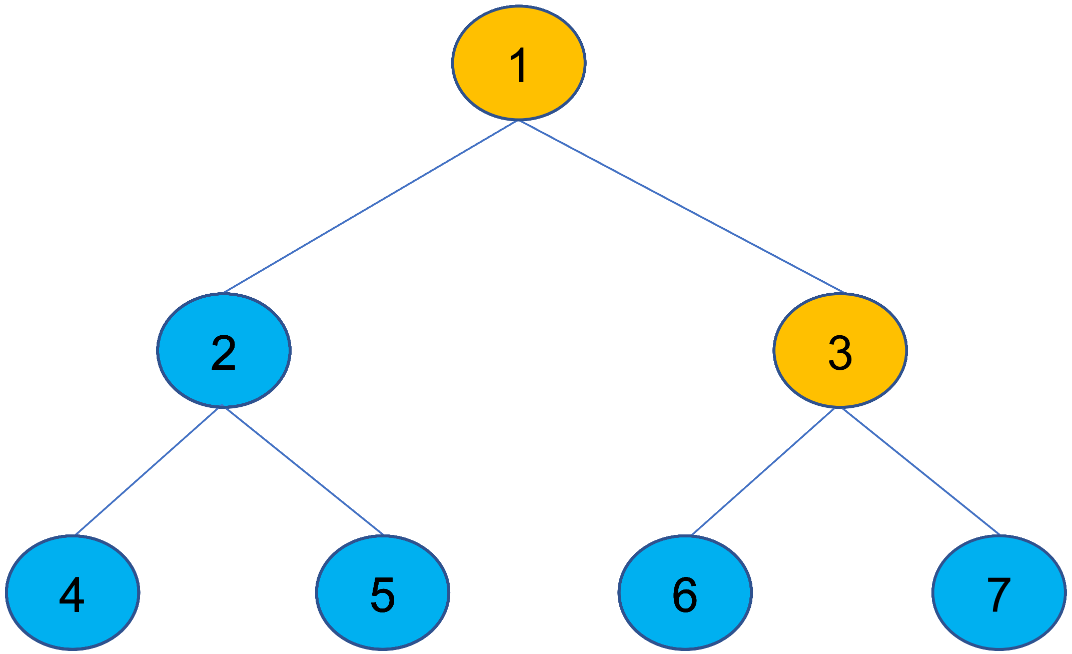


```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2] := 0
        await(arrive[3]  = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

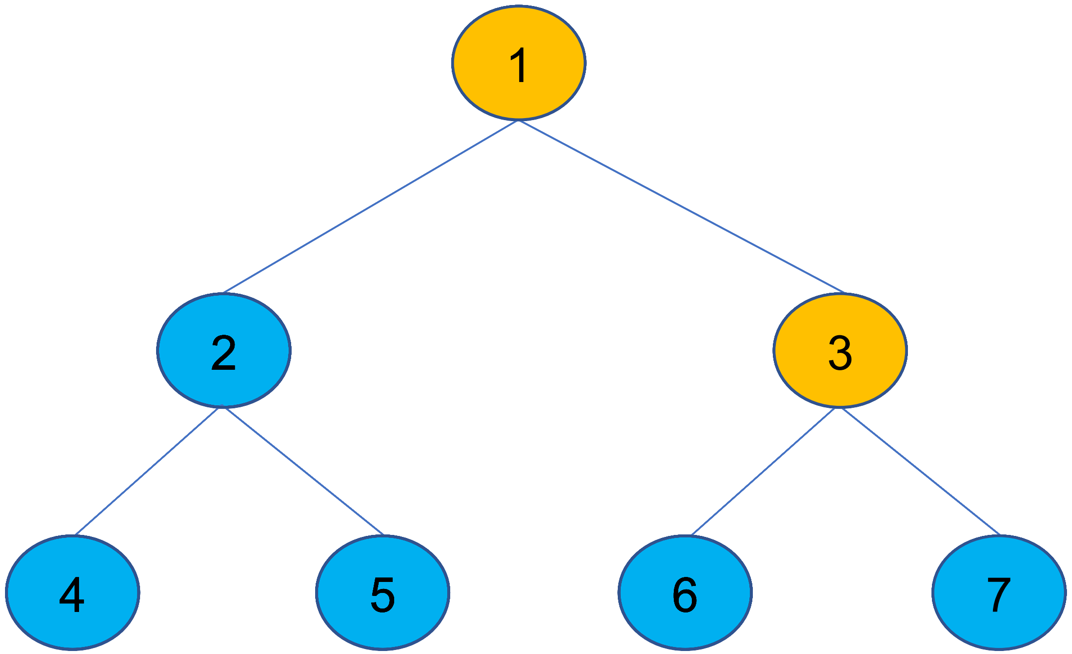


```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

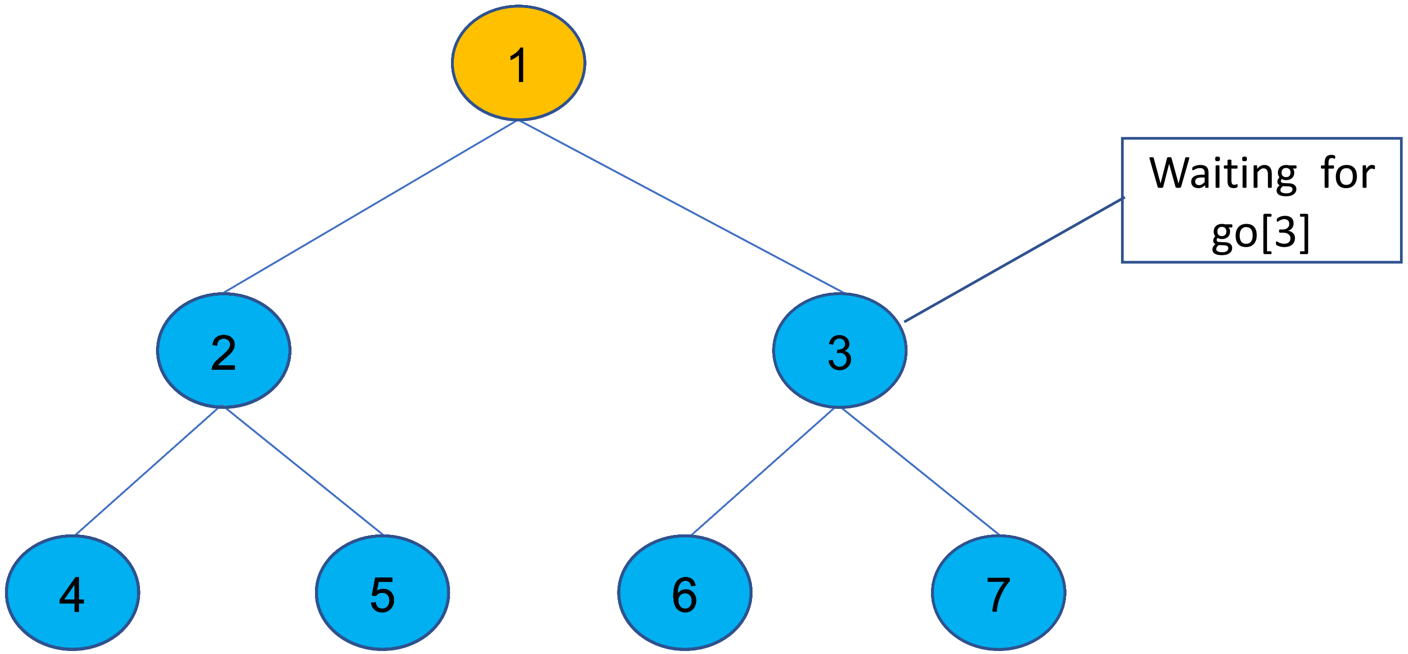


arrive	0	1	0	0	0	0
go						
	2	3	4	5	6	7

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                              // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                 // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                     // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



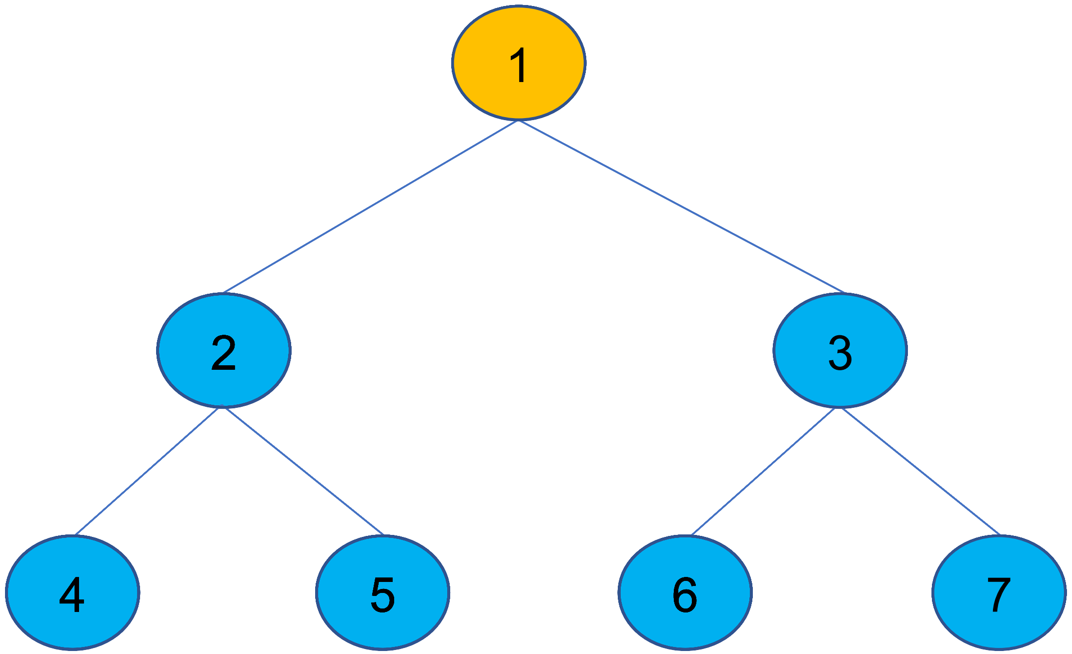
Waiting for go[3]

```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0	1	0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



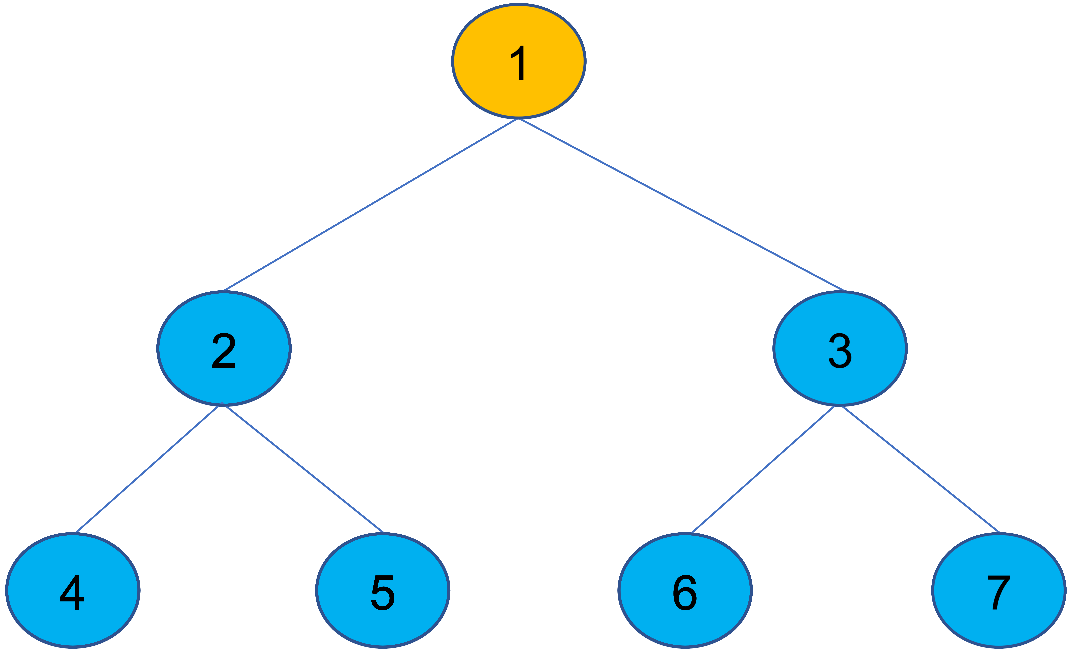
```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0	1	0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

P_1 zeros arrive[3]



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go						
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shared   arrive[2..n]: array of atomic bits, initial values = 0
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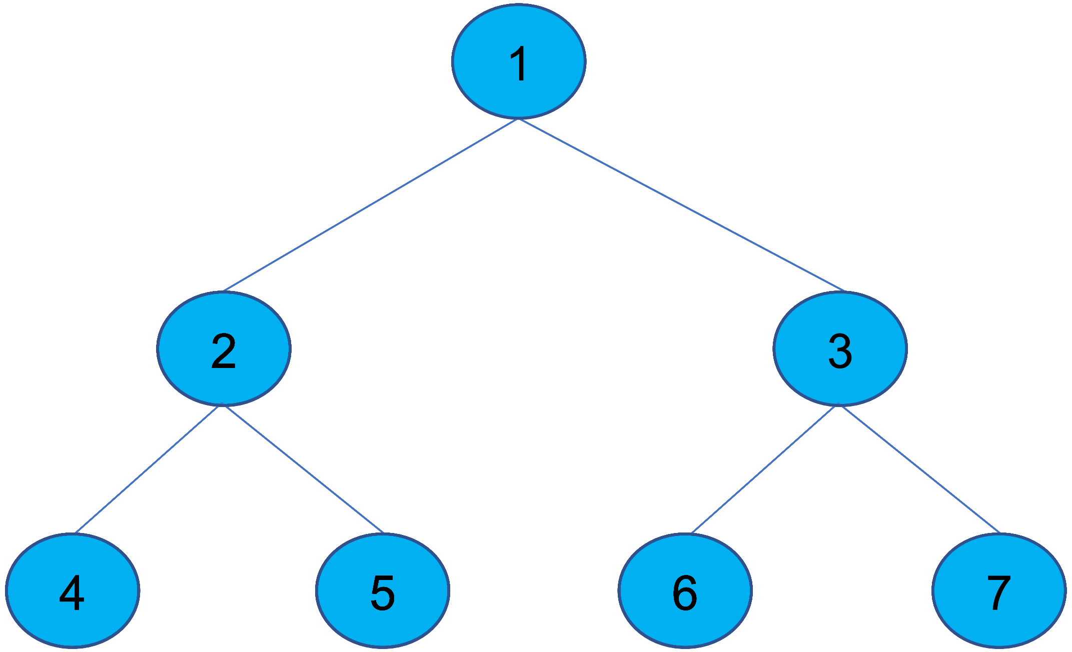
A Tree-based Barrier
Example Run for n=7 threads



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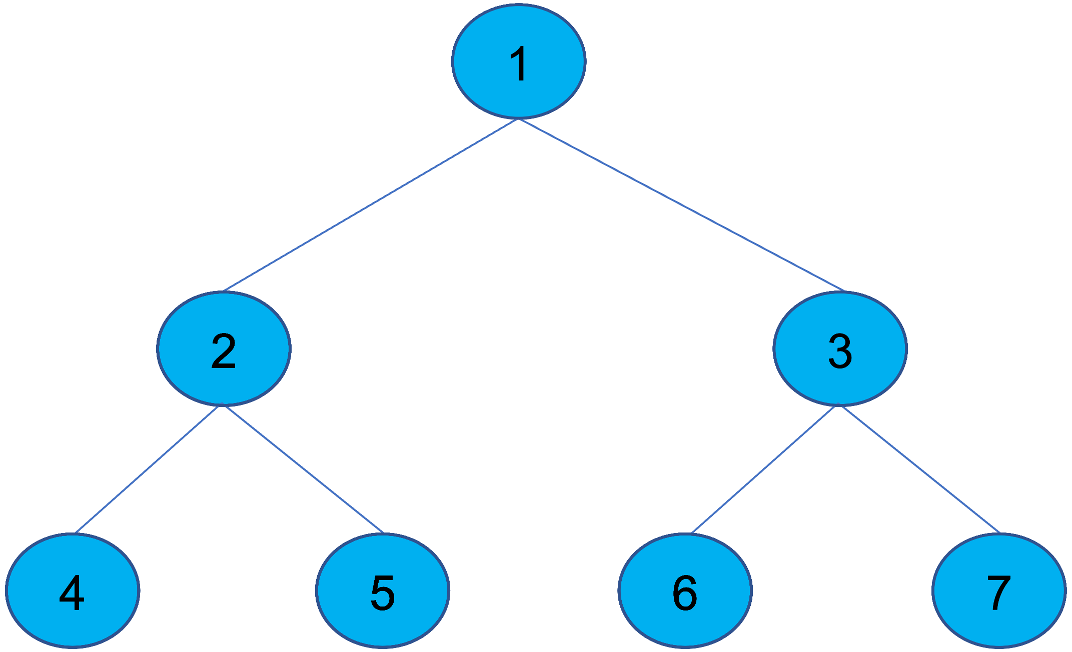

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At this point all non-root threads in some await(go) case

A Tree-based Barrier
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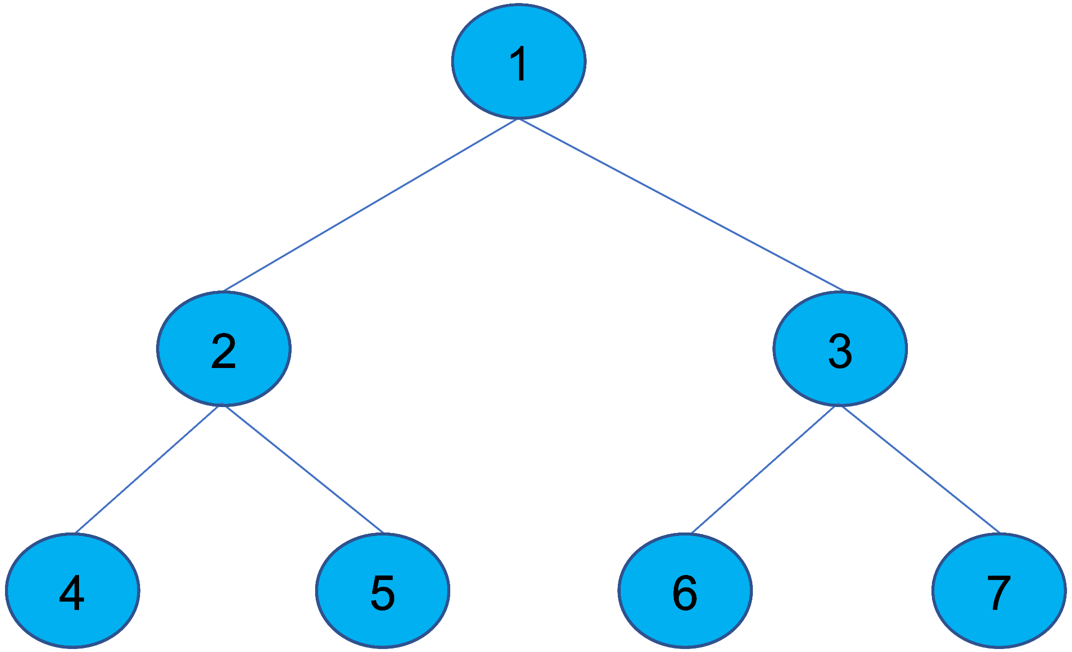

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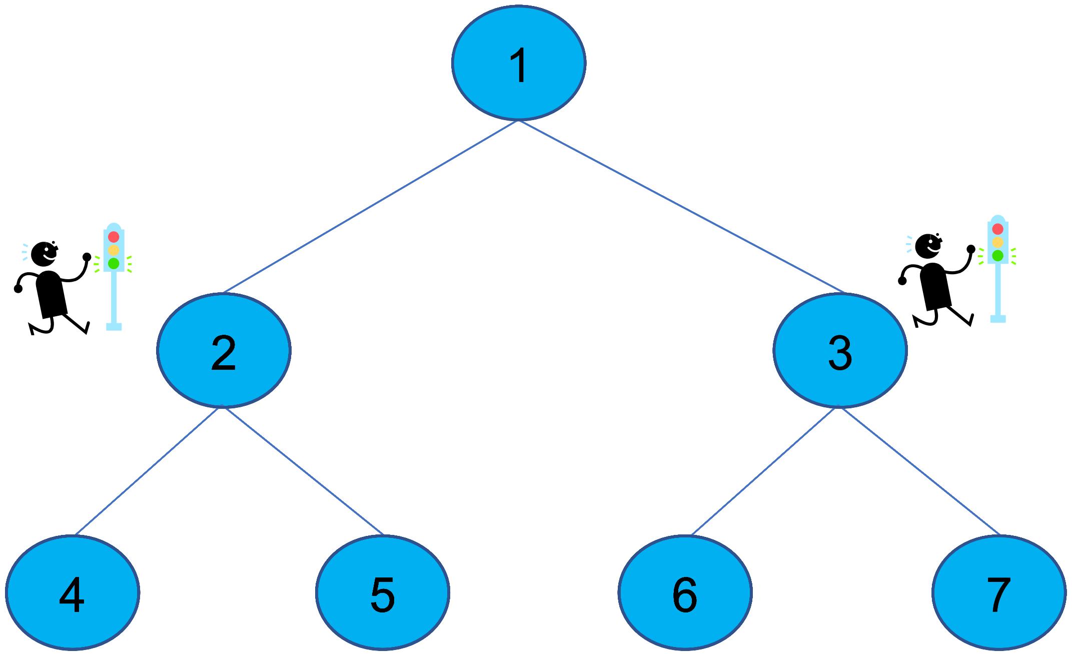

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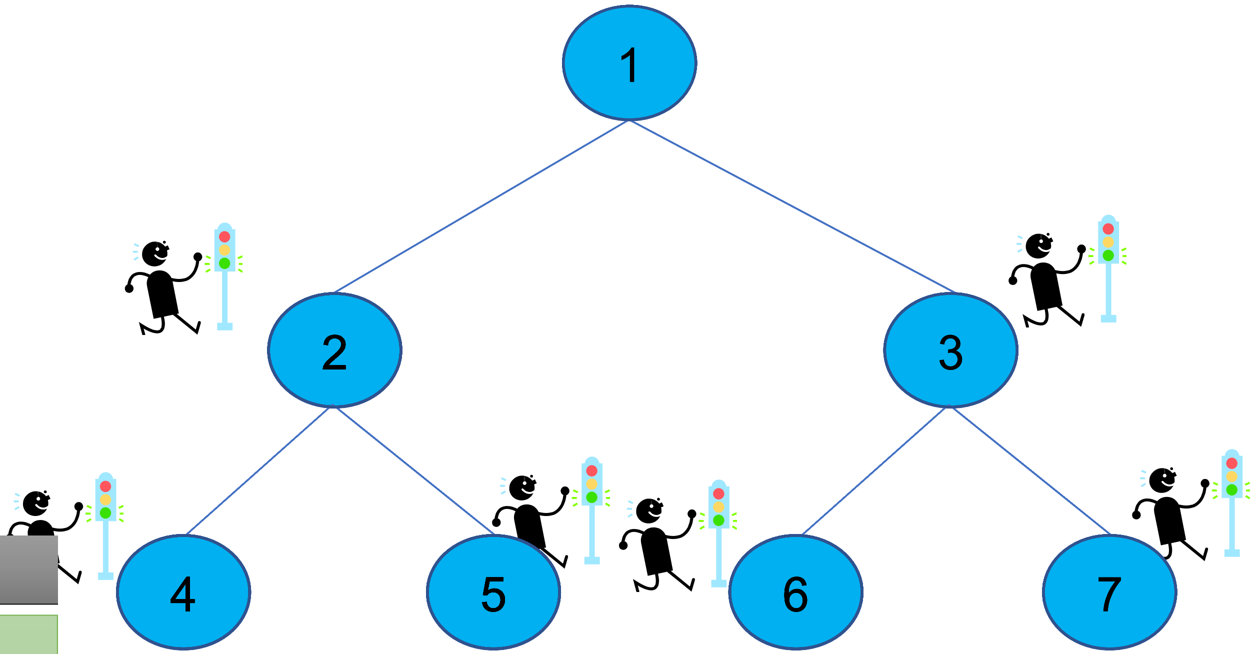

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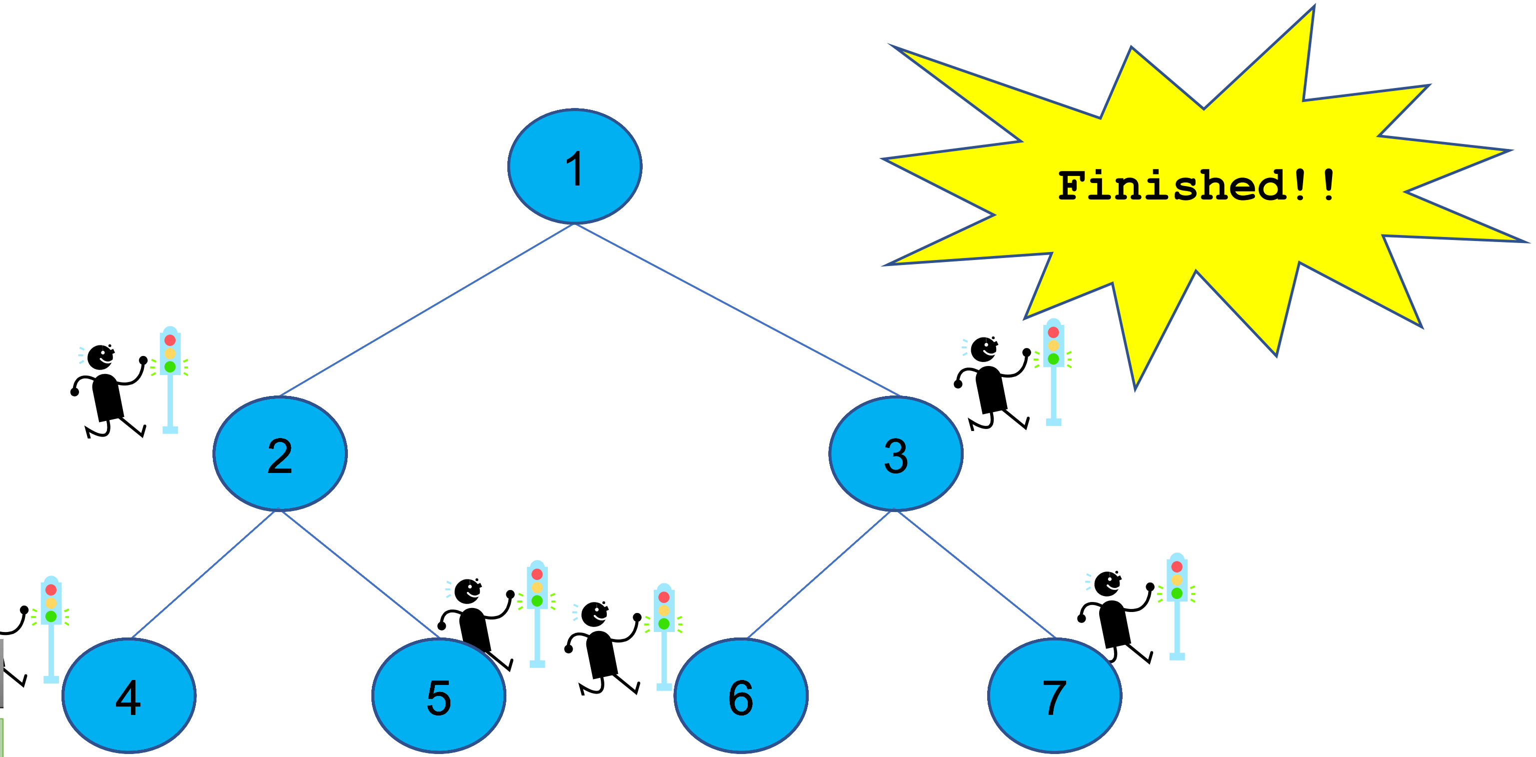

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Tree Barrier Tradeoffs

- Pros:

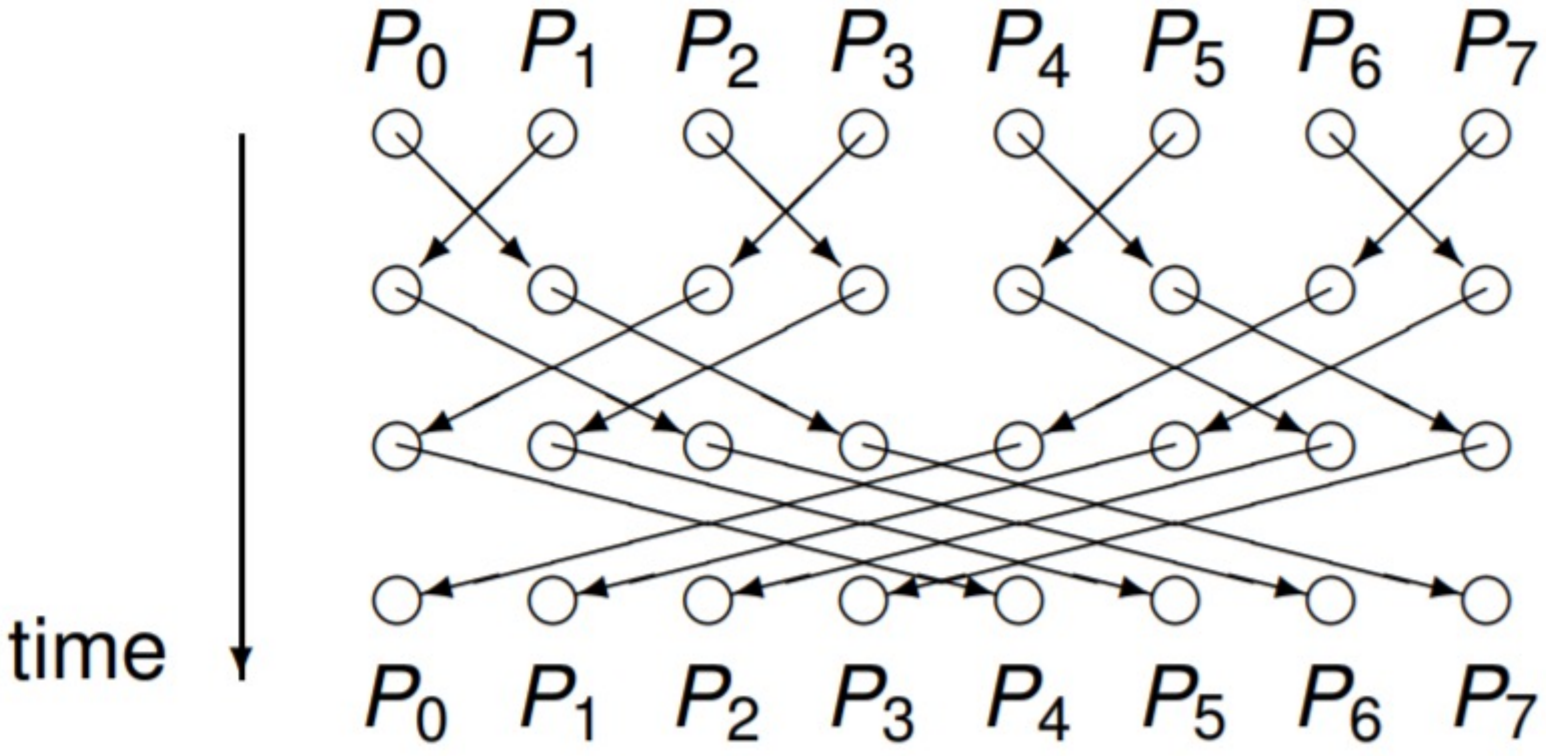
- Cons:

Tree Barrier Tradeoffs

- Pros:
  - Low shared memory contention
    - No wait object is shared by more than 2 processes
    - Good for larger n
  - Fast – information from the root propagates after log(n) steps
  - Can use only atomic primitives (no special objects)
  - On some models:
    - each process spins on a locally accessible bit
    - # (remote memory ref.) = O(1) per process
- Cons:
  - Shared memory space complexity – O(n)
  - Asymmetric –all the processes don’t the same amount of work
  - Corner cases for n != 2^k-1

Butterfly Barrier

Butterfly Barrier



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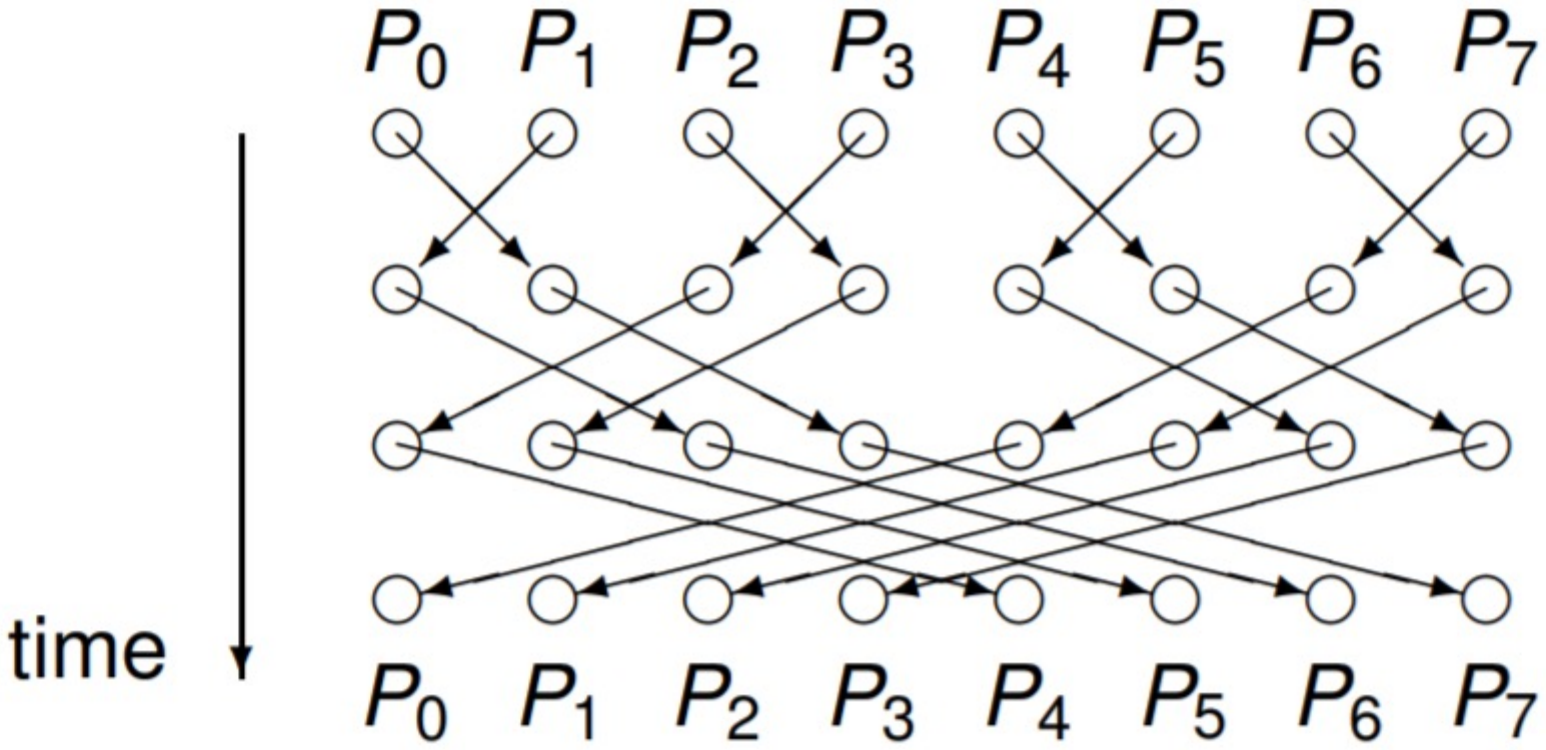
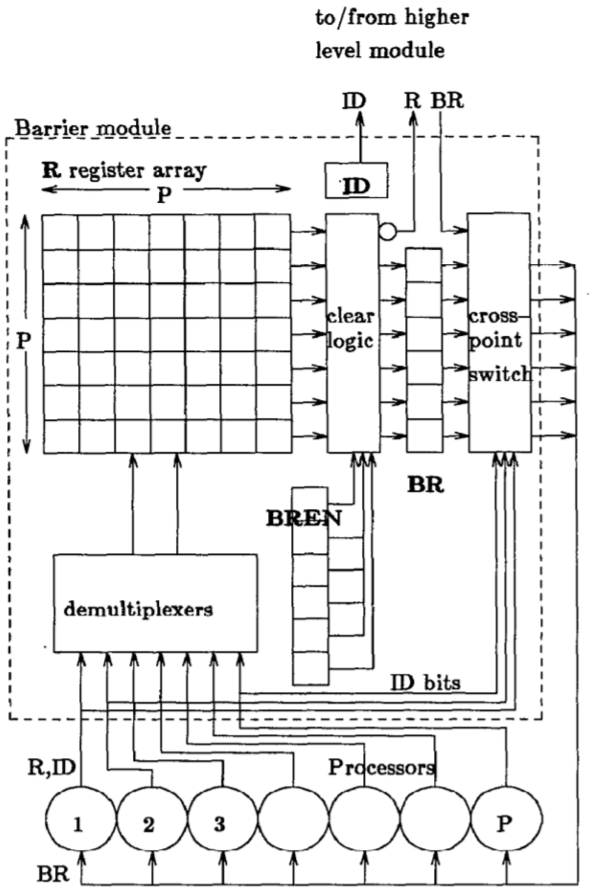


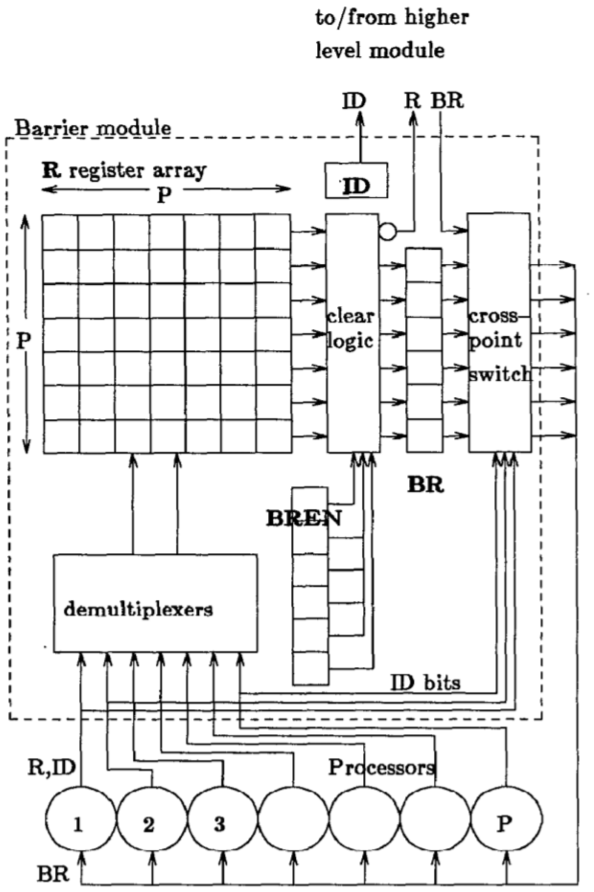
- When would this be preferable?

Hardware Supported Barriers



CPU

Hardware Supported Barriers



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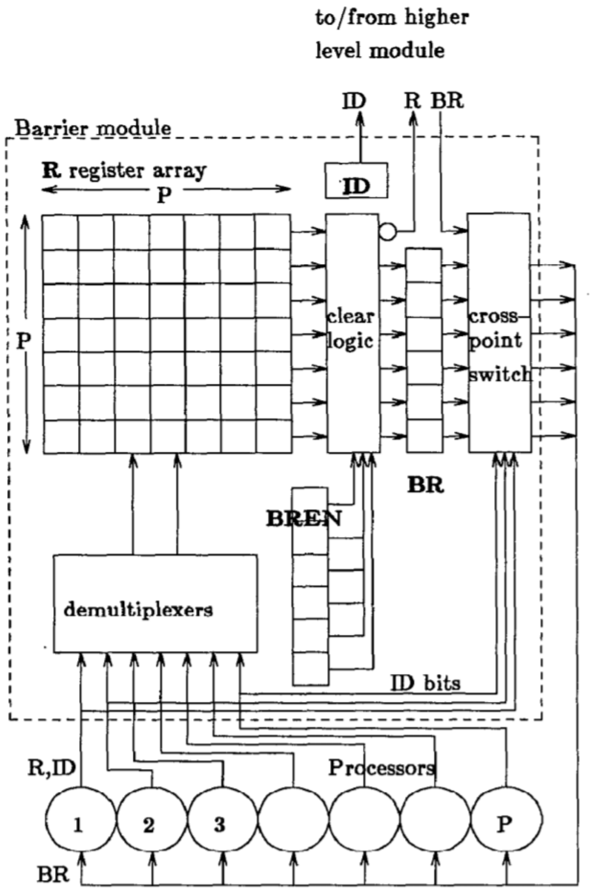
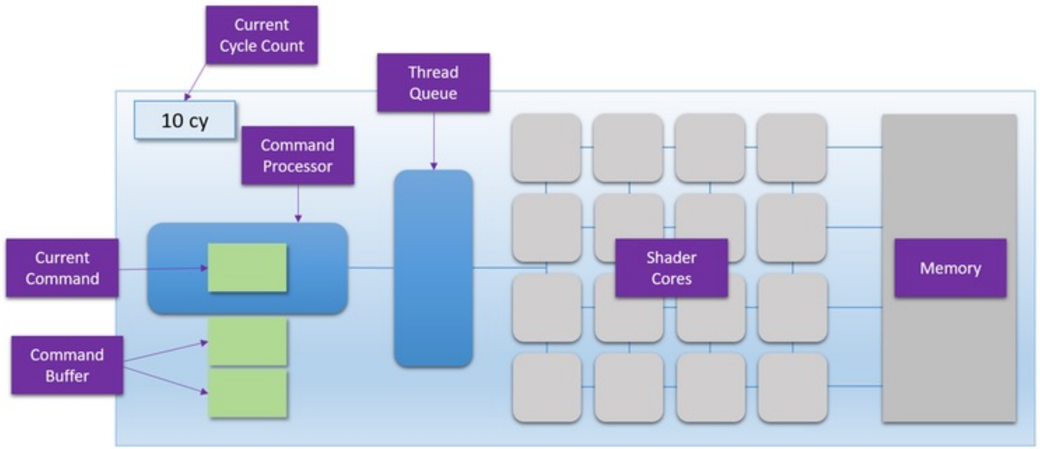


CPU



GPU

- When would this be useful?

Barriers Summary

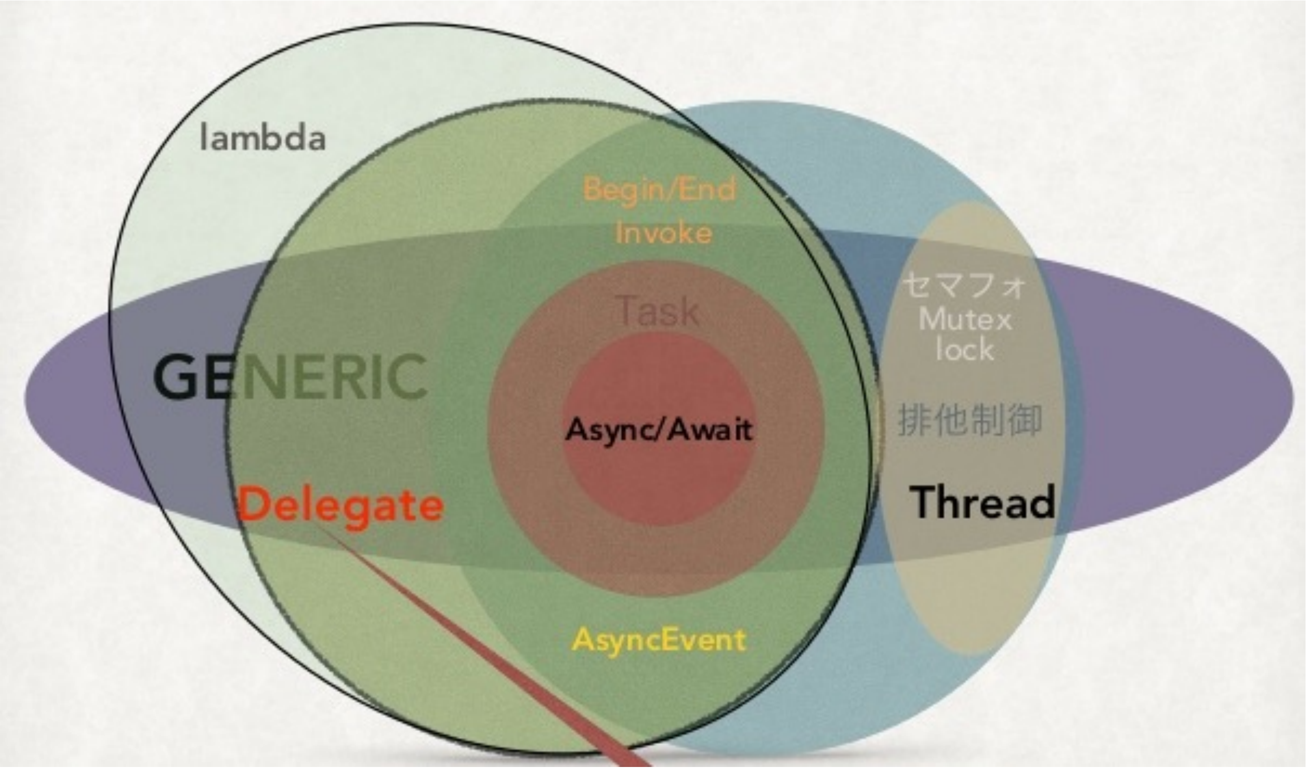
Seen:

- Semaphore-based barrier
- Simple barrier
    - Based on atomic fetch-and-increment counter
- Local spinning barrier
    - Based on atomic fetch-and-increment counter and go array
- Tree-based barrier

Not seen:

- Test-and-Set barriers
    - Based on test-and-test-and-set objects
    - One version without memory initialization
- See-Saw barrier
- Book has condition barriers

Asynchronous Programming
Events, Promises, and Futures



Programming Models for Concurrency

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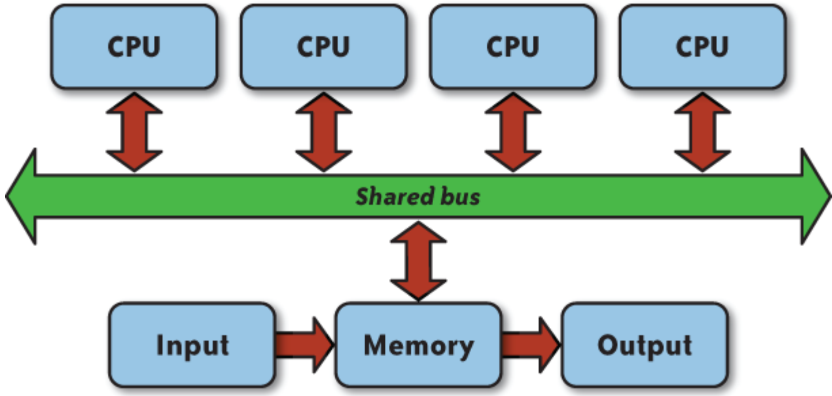

Programming Models for Concurrency

- Hardware execution model:
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- Programming model dimensions:
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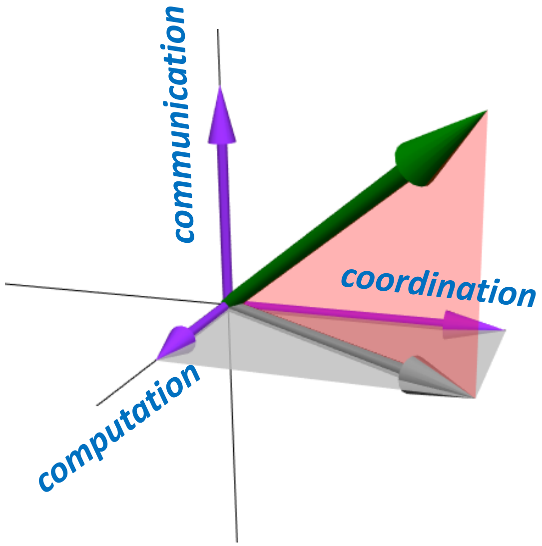

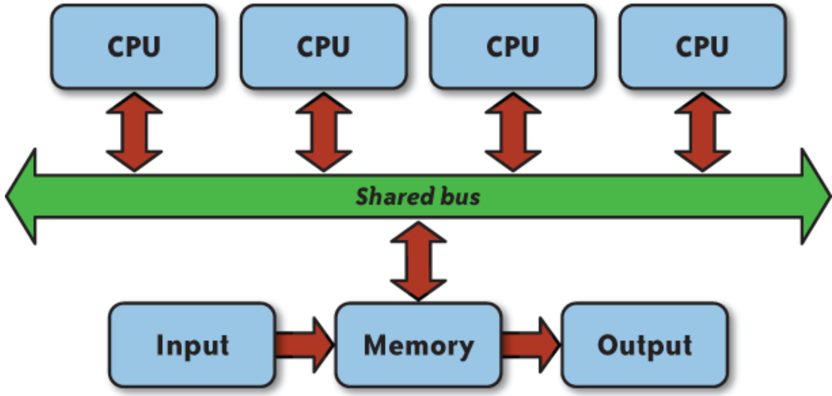

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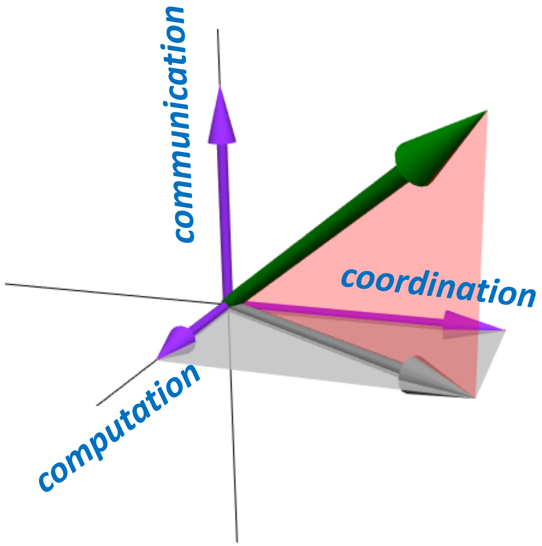

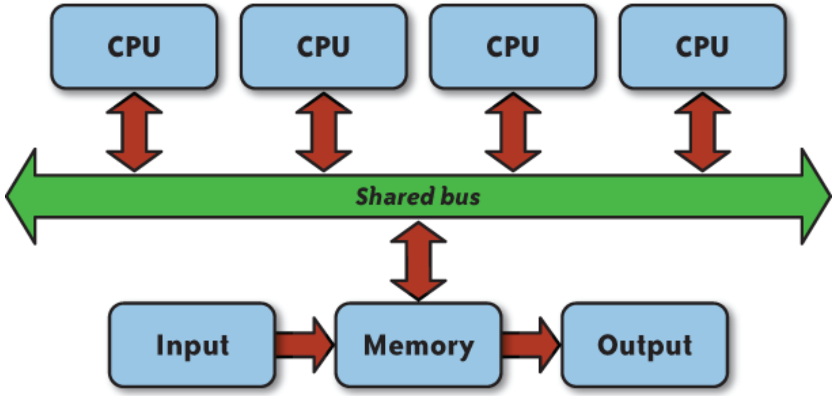

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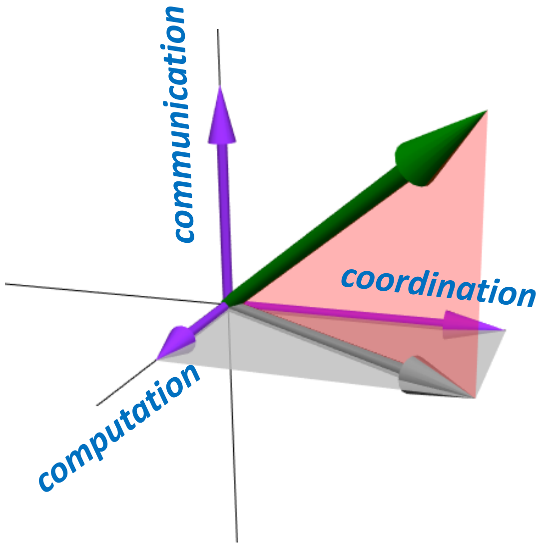

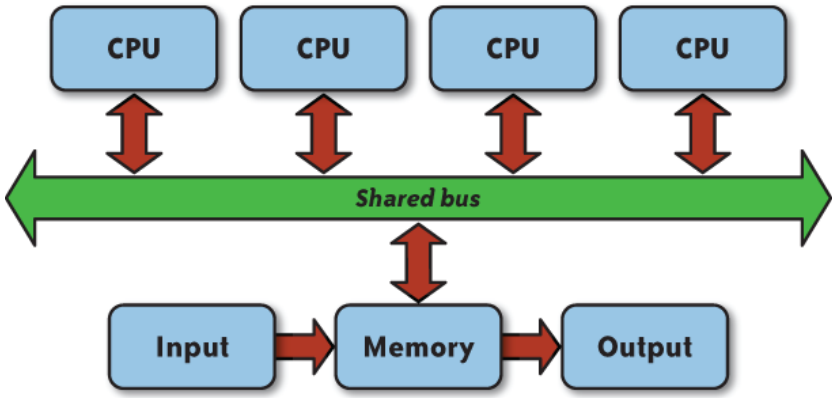

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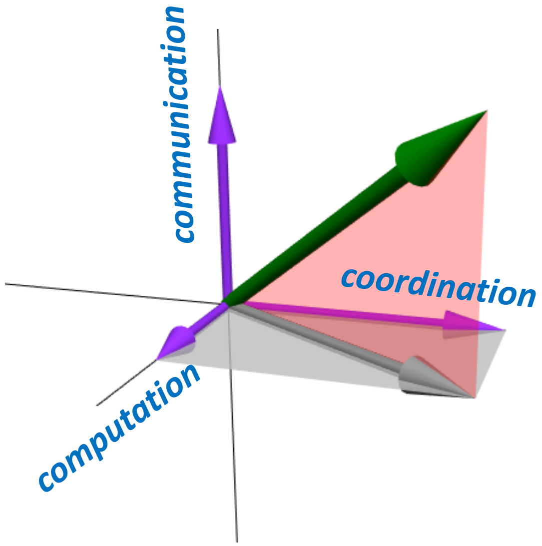
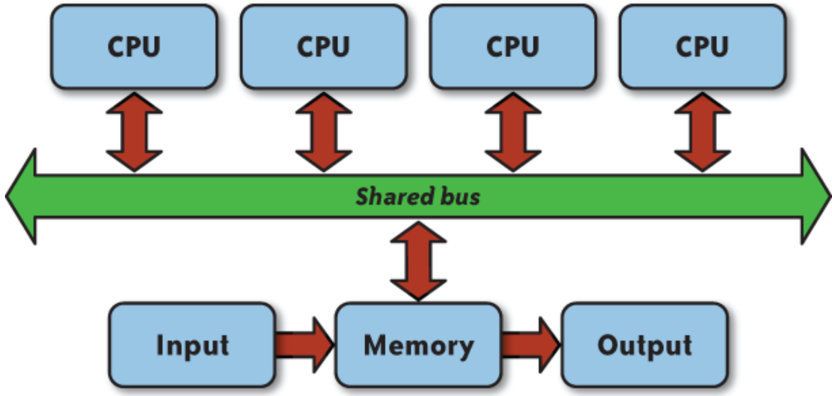
Futures & Promises touch all three dimension





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- Values *that will eventually become available*
- Time-dependent states:
  - **Completed/determined**
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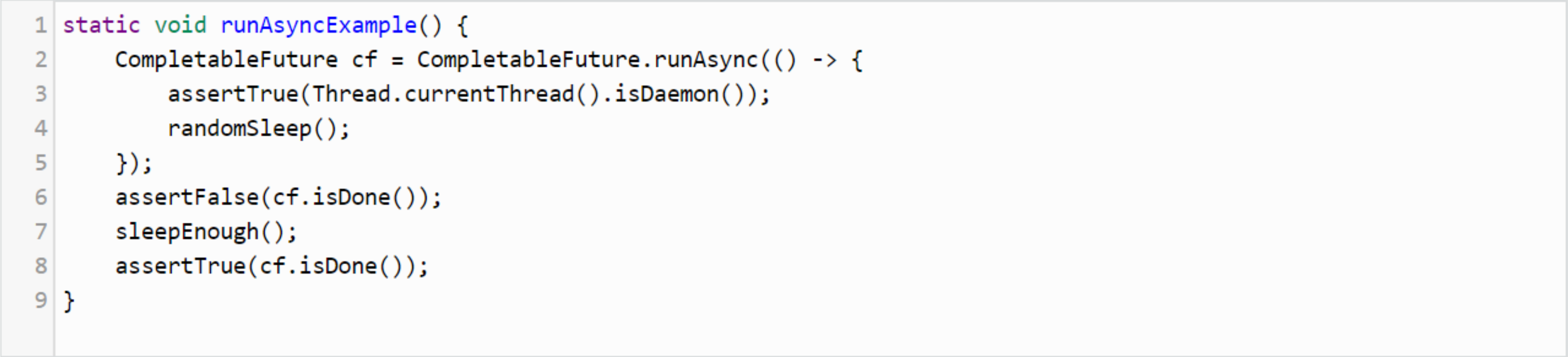
- Construct (future X)
  - immediately returns value
  - concurrently executes X

Java Example



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static void runAsyncExample() {
    CompletableFuture cf = CompletableFuture.runAsync(() -> {
        assertTrue(Thread.currentThread().isDaemon());
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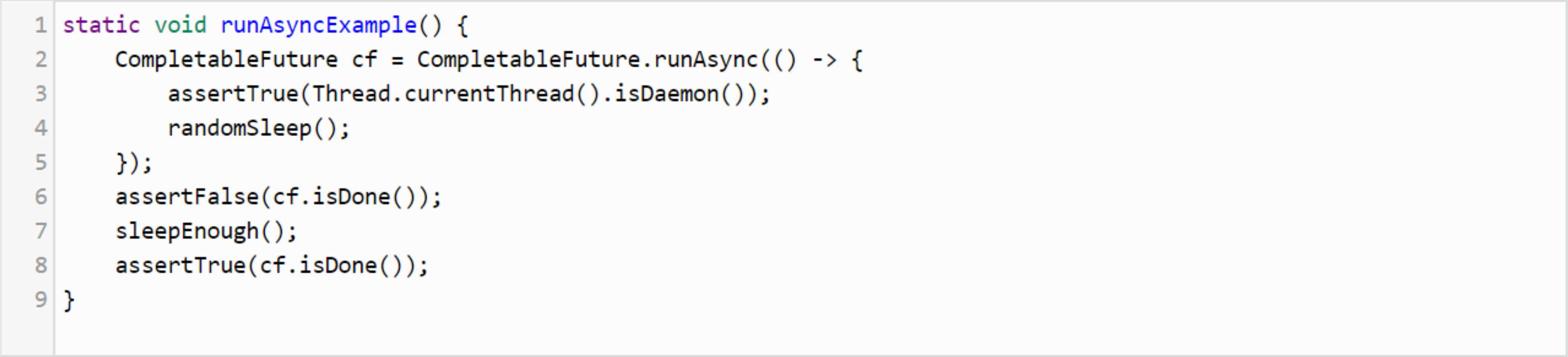

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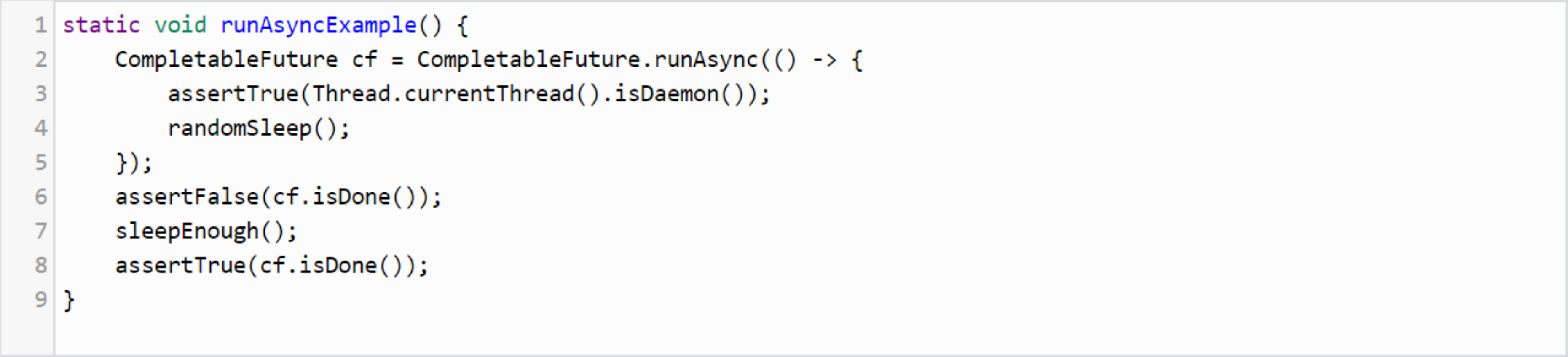

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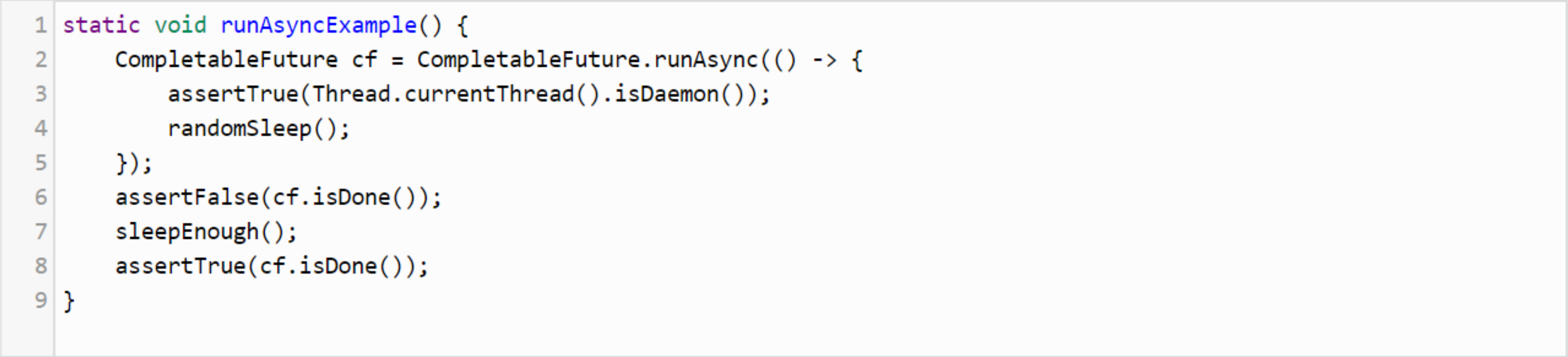

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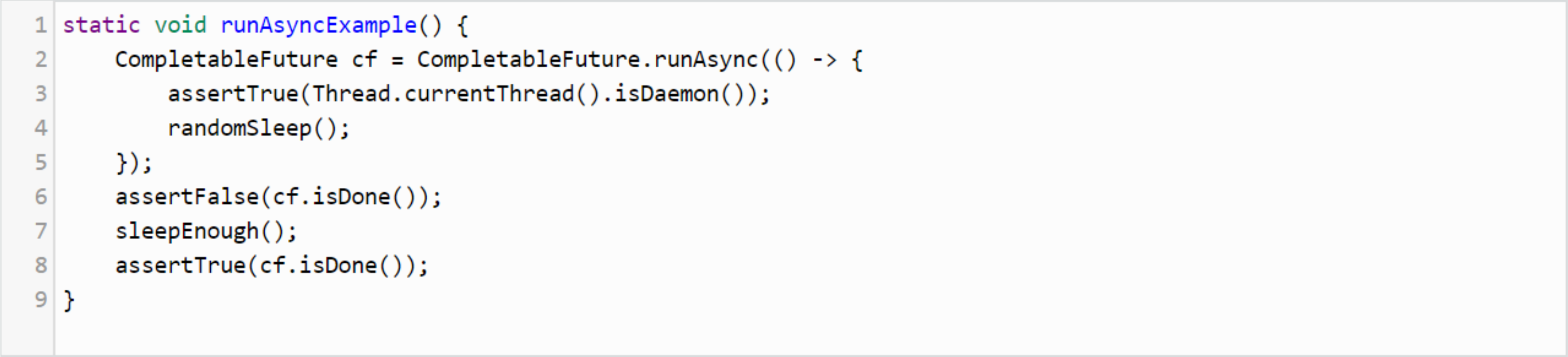

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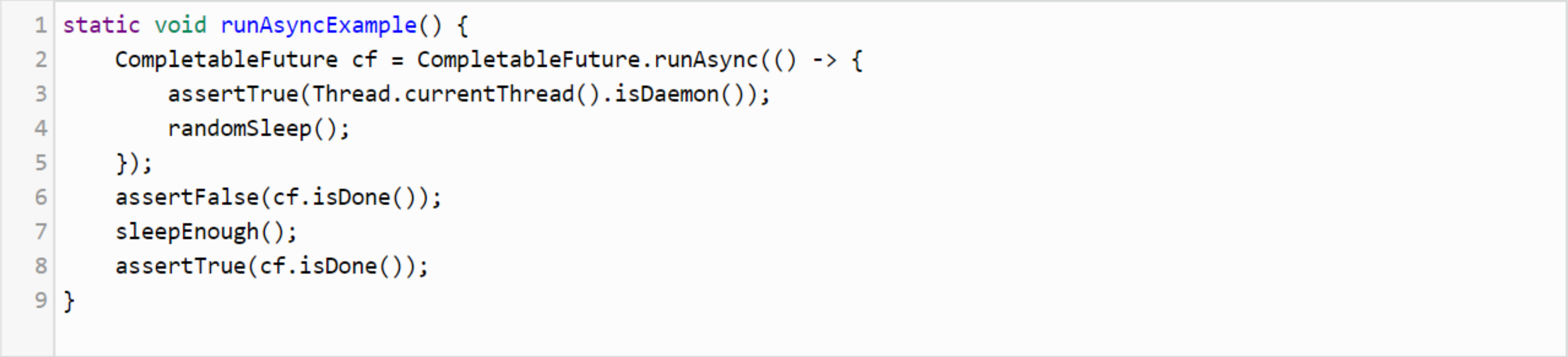

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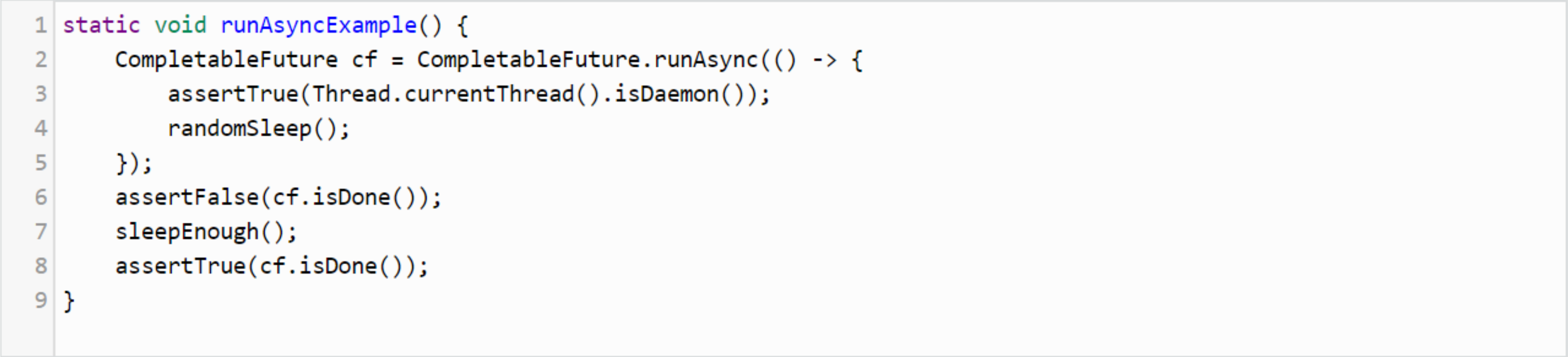

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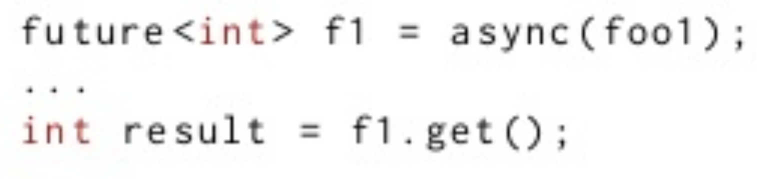
- Where (on what thread) does the lambda expression run?

Futures and Promises:

Why two kinds of objects?



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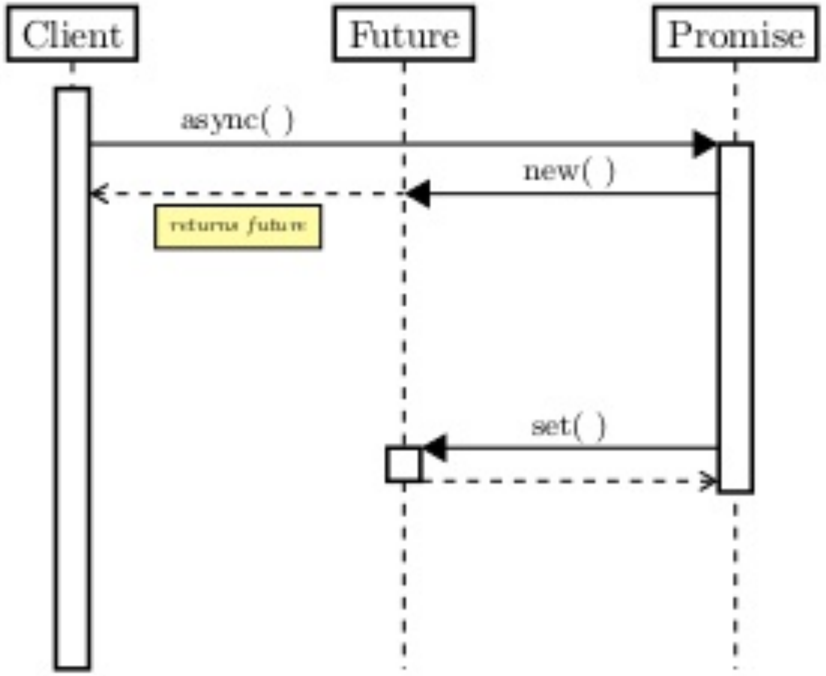

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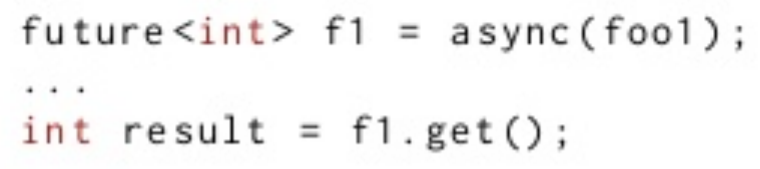

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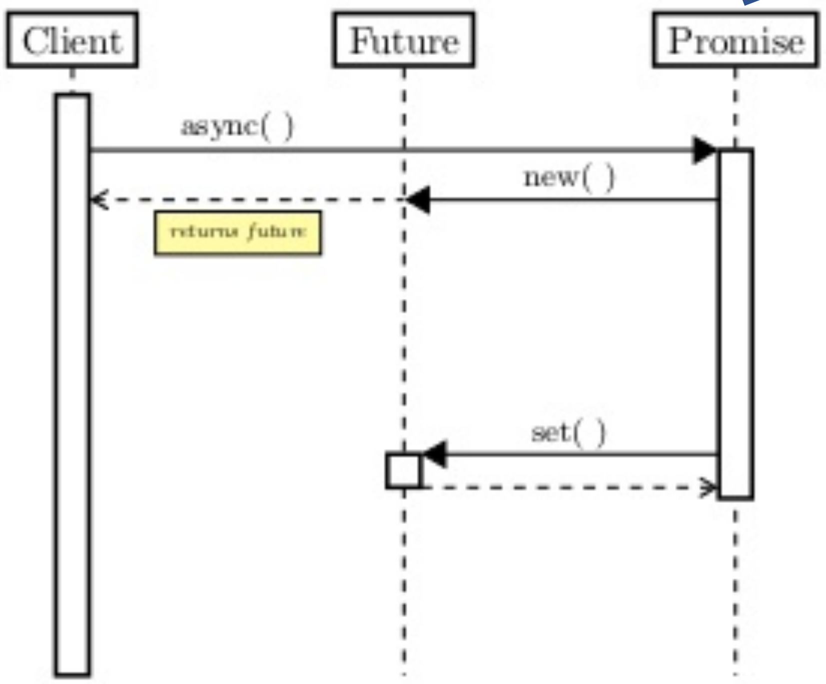

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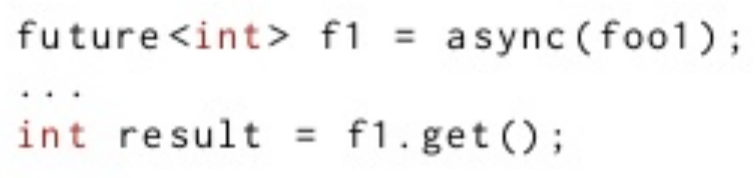

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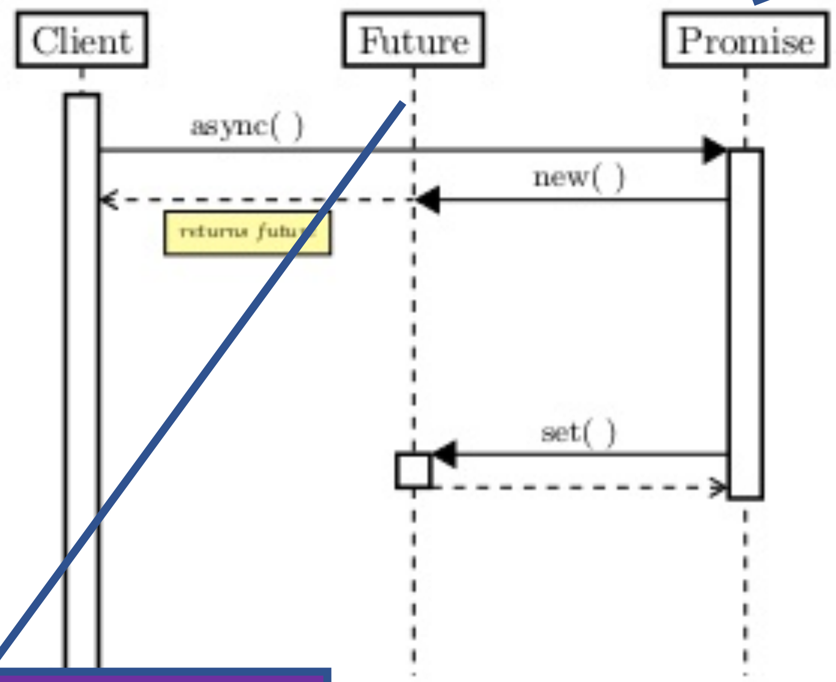
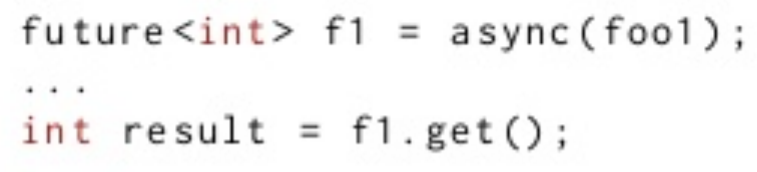


Future: encapsulation (something to give caller)

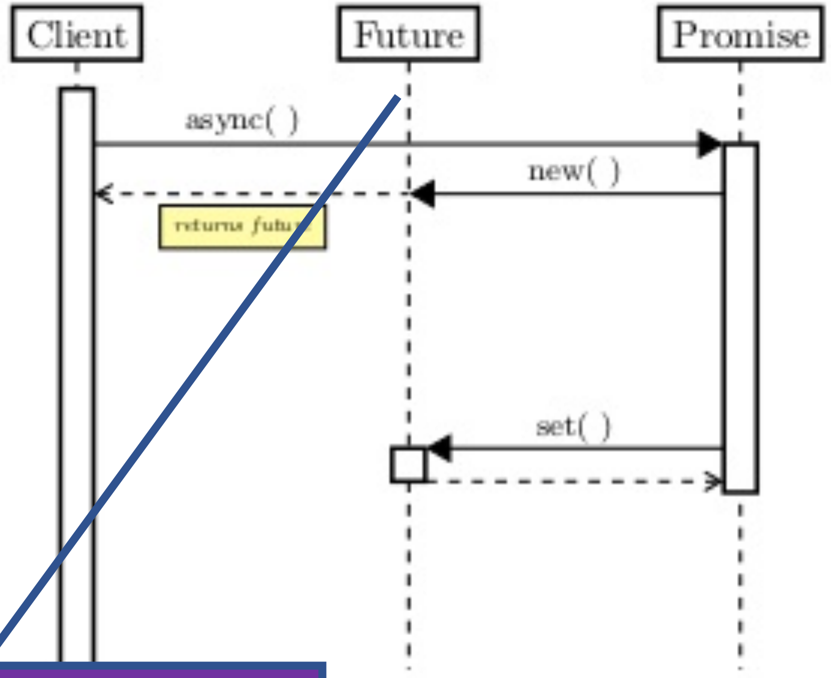
Futures and Promises:

Why two kinds of objects?

Promise: “thing to be done”



```
future<int> f1 = async(foo1);
...
int result = f1.get();
```

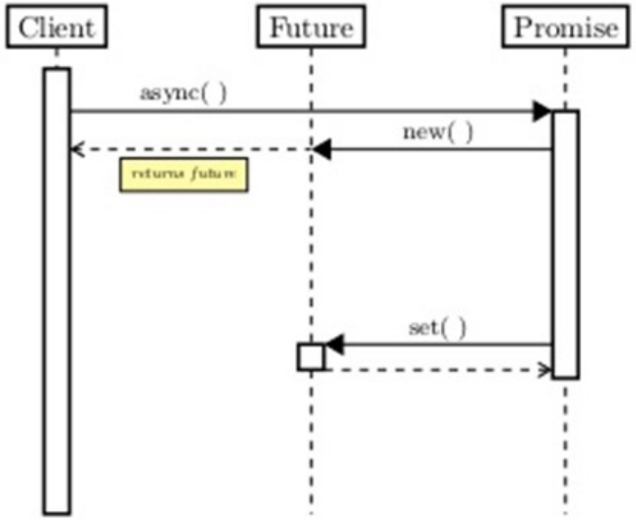


Future: encapsulation
(something to give caller)

`Promise to do` `something in the future`

Futures vs Promises

- **Future:** read-only reference to uncompleted value
- **Promise:** single-assignment variable that the future refers to
- Promises *complete* the future with:
    - Result with success/failure
    - Exception



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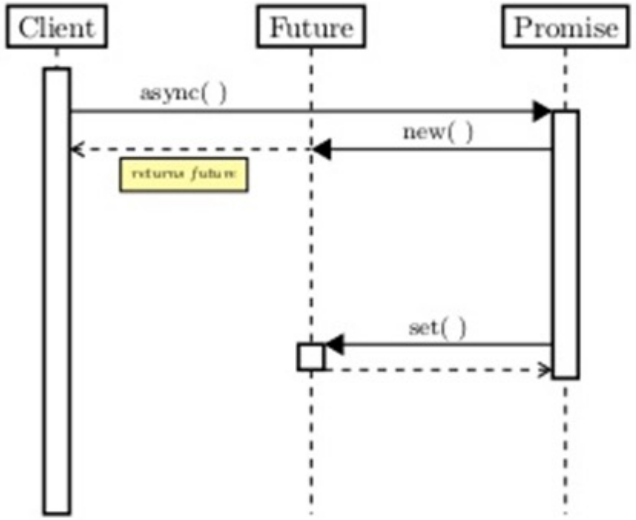
Language	Promise	Future
Algol	Thunk	Address of async result
Java	Future<T>	CompletableFuture<T>
C#/.NET	TaskCompletionSource<T>	Task<T>
JavaScript	Deferred	Promise
C++	std::promise	std::future



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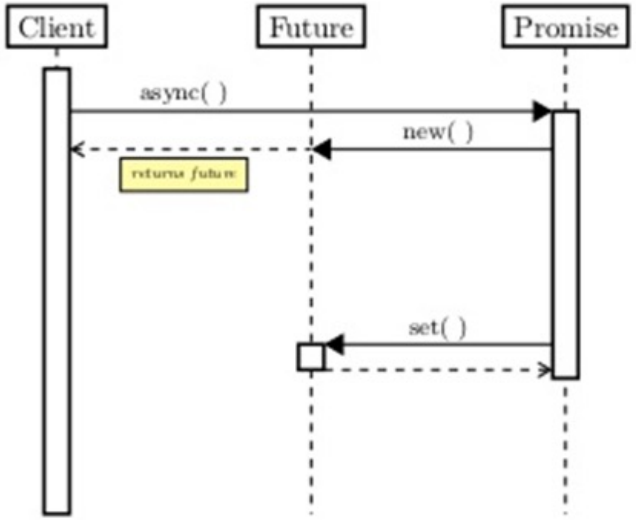

Futures vs Promises

Mnemonic:
Promise to ***do*** something
Make a promise ***for*** the future

- **Future:** read-only reference to uncompleted value
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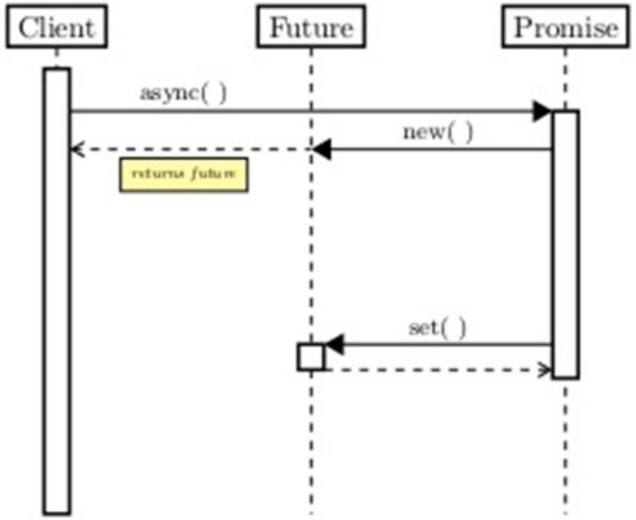

Putting Futures in Context

My unvarnished opinion

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Putting Futures in Context

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Futures:

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  - Compiler: abstractions are ***language-level objects***
  - Runtime: scheduler, task queues, thread-pools are ***transparent***

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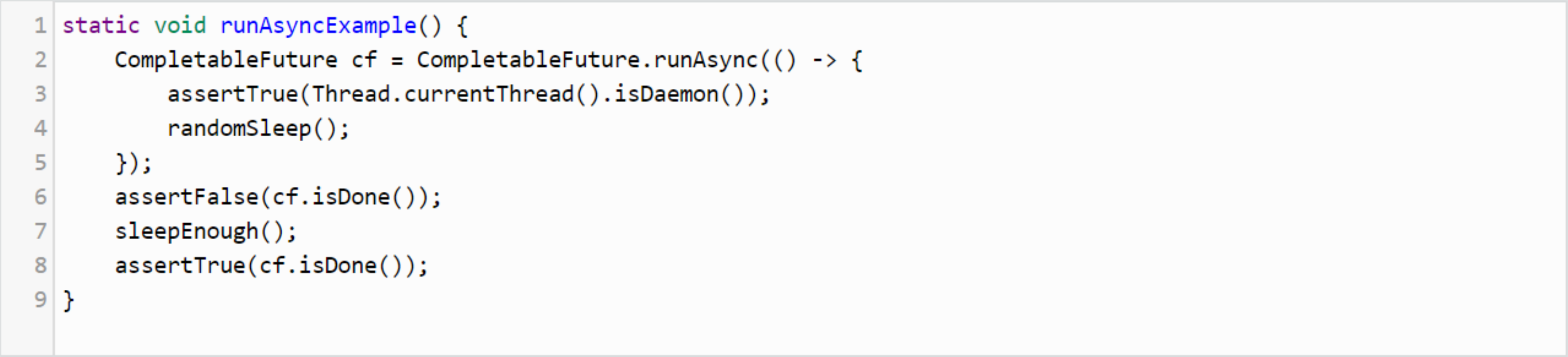

```java
static void runAsyncExample() {
    CompletableFuture cf = CompletableFuture.runAsync(() -> {
        assertTrue(Thread.currentThread().isDaemon());
        randomSleep();
    });
    assertFalse(cf.isDone());
    sleepEnough();
    assertTrue(cf.isDone());
}
```

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Compromise Programming Model between:

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My unvarnished opinion

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Compromise Programming Model between:

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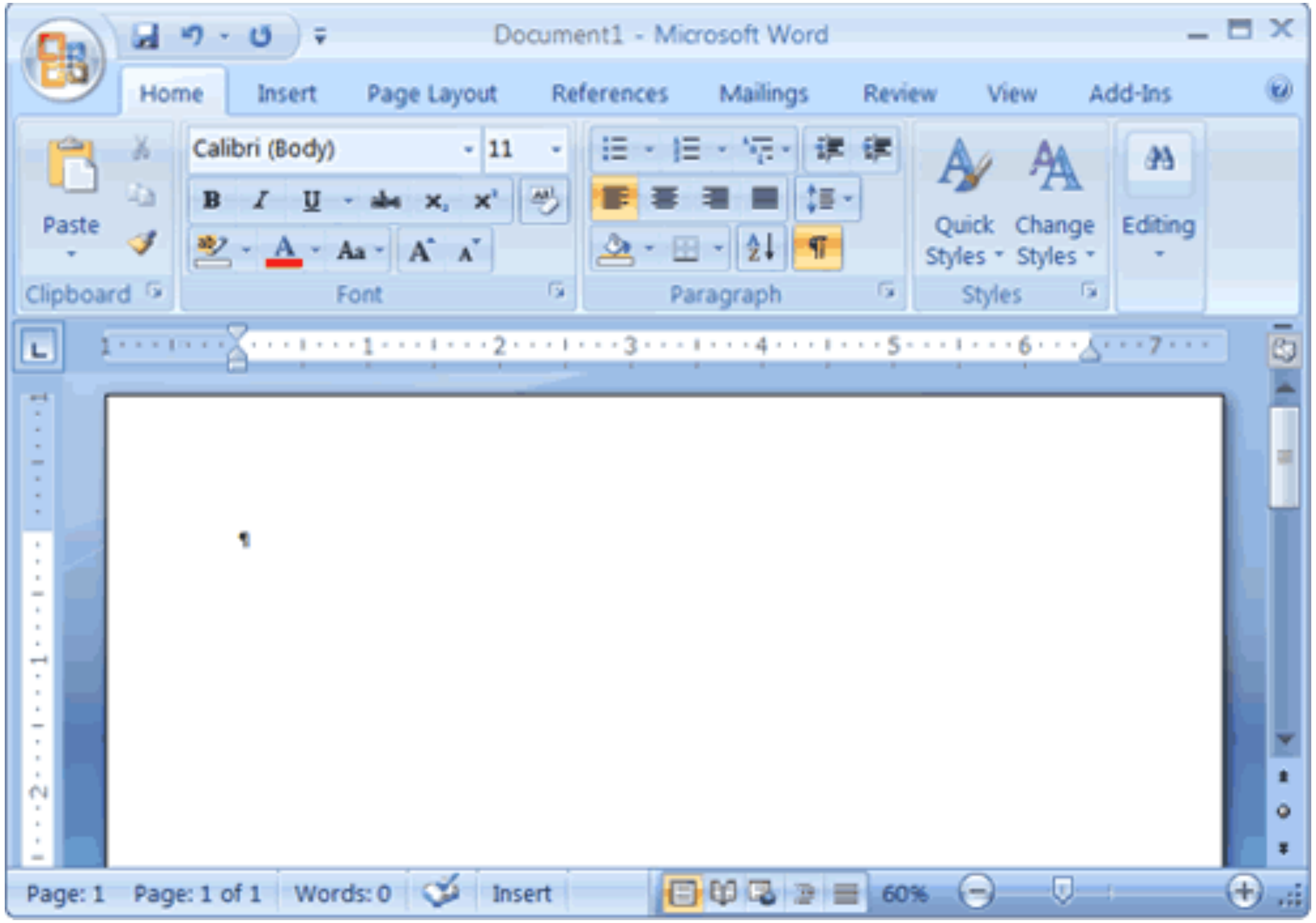
Compromise Programming Model between:

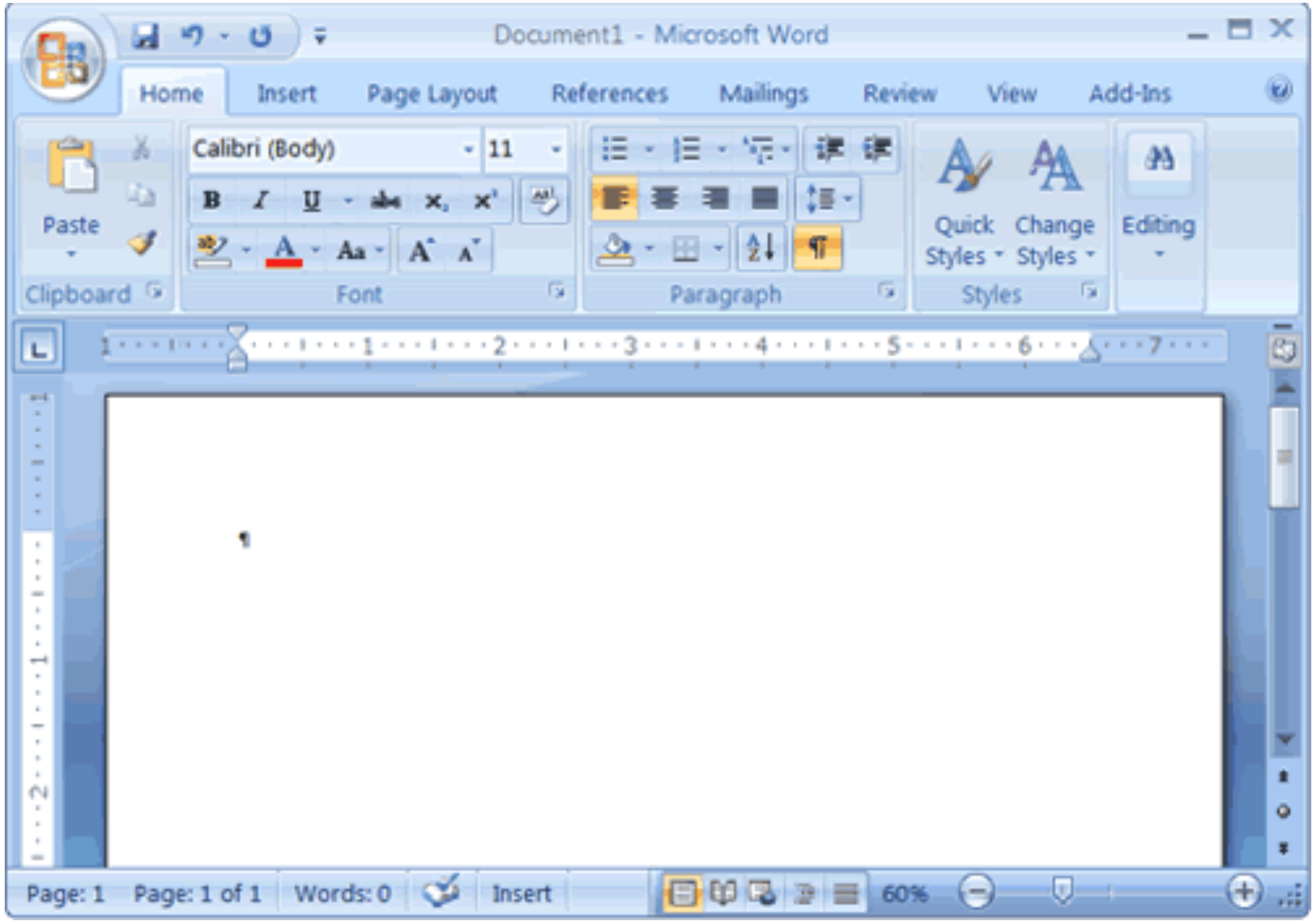
- Event-based programming
- Thread-based programming

Events vs. Threads!

GUI Programming

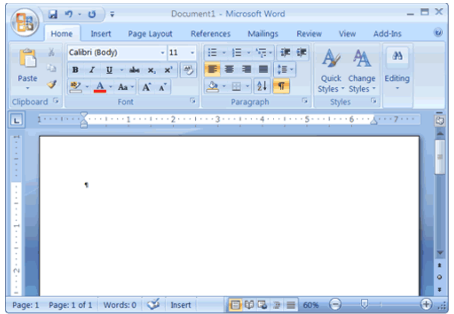


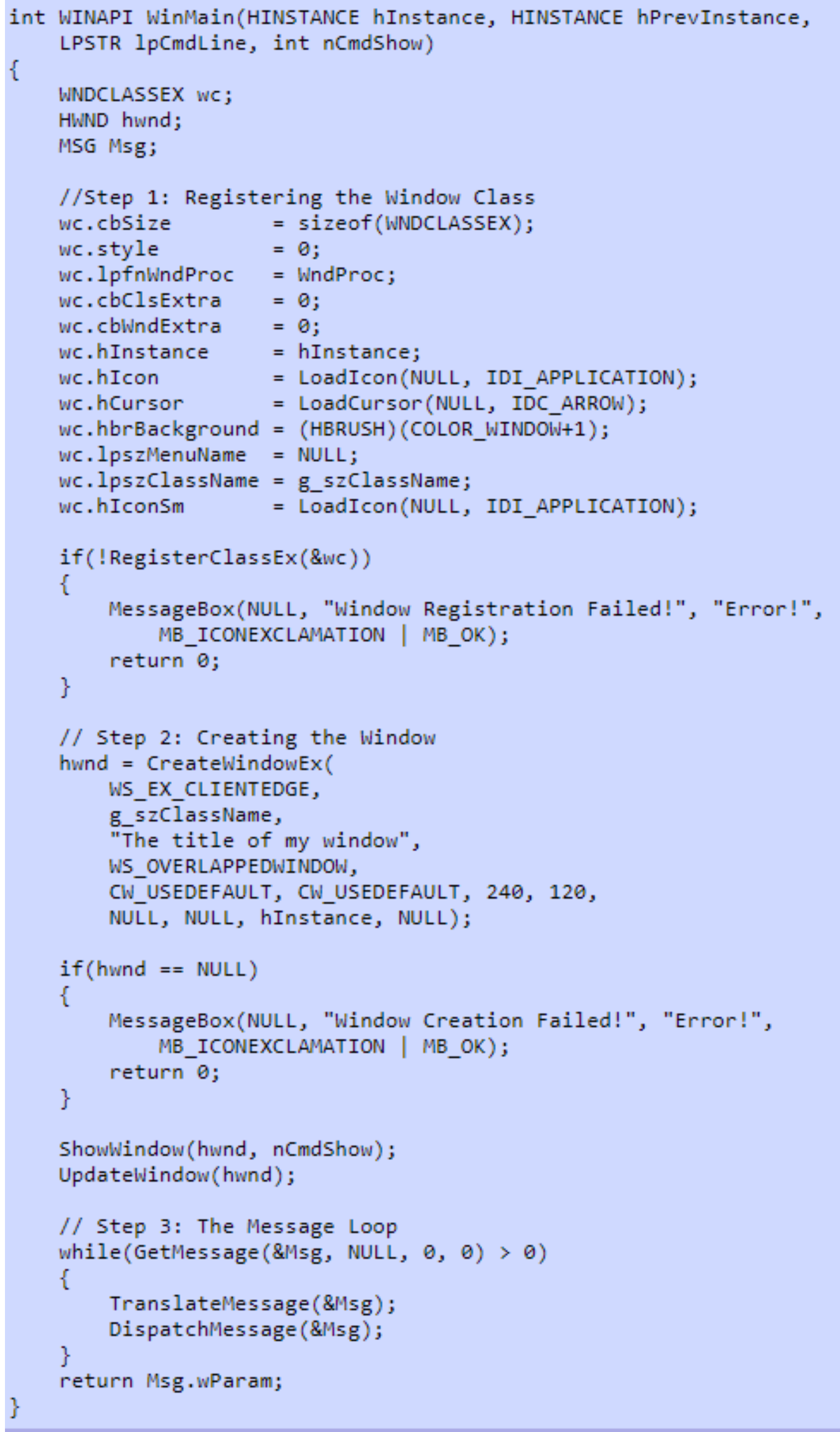
GUI Programming



```
do {
  WaitForSomething();
  RespondToThing();
} until(forever);
```

GUI Programming





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{
    WNDCLASSEX wc;
    HWND hwnd;
    MSG Msg;

    //Step 1: Registering the Window Class
    wc.cbSize        = sizeof(WNDCLASSEX);
    wc.style         = 0;
    wc.lpfnWndProc   = WndProc;
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    wc.hInstance     = hInstance;
    wc.hIcon         = LoadIcon(NULL, IDI_APPLICATION);
    wc.hCursor       = LoadCursor(NULL, IDC_ARROW);
    wc.hbrBackground = (HBRUSH)(COLOR_WINDOW+1);
    wc.lpszMenuName  = NULL;
    wc.lpszClassName = g_szClassName;
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    if(!RegisterClassEx(&wc))
    {
        MessageBox(NULL, "Window Registration Failed!", "Error!",
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    }

    // Step 2: Creating the Window
    hwnd = CreateWindowEx(
        WS_EX_CLIENTEDGE,
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    while(GetMessage(&Msg, NULL, 0, 0) > 0)
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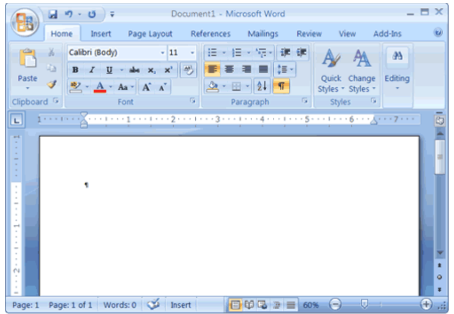
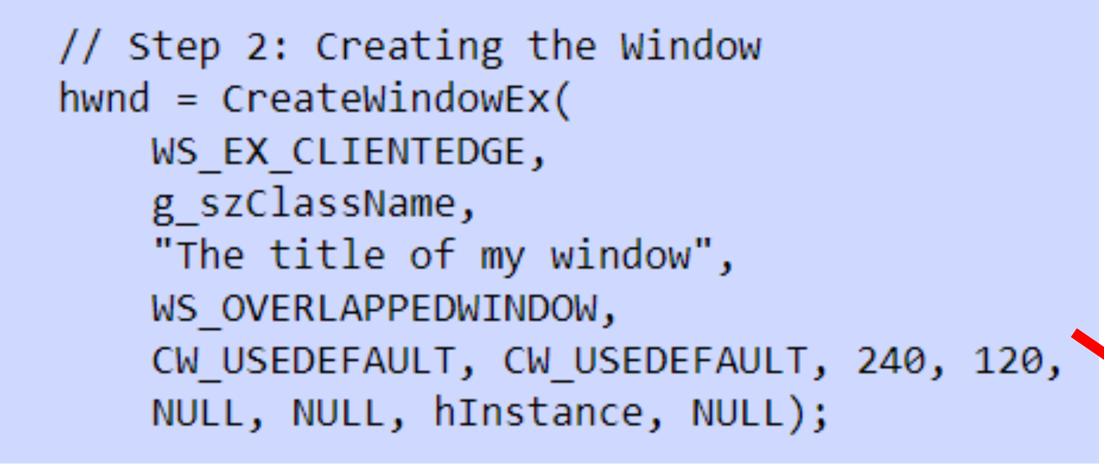


GUI Programming



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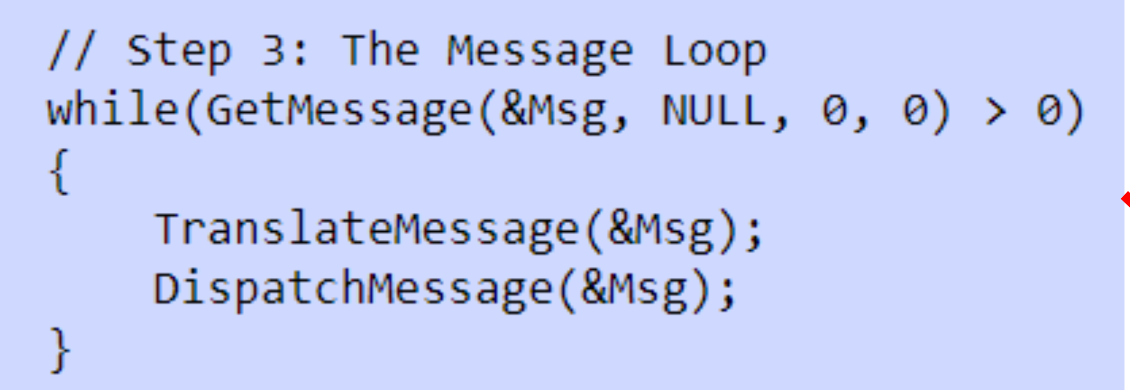

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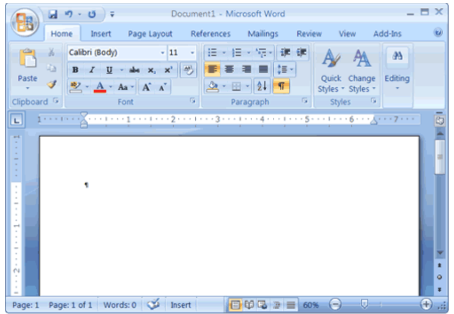

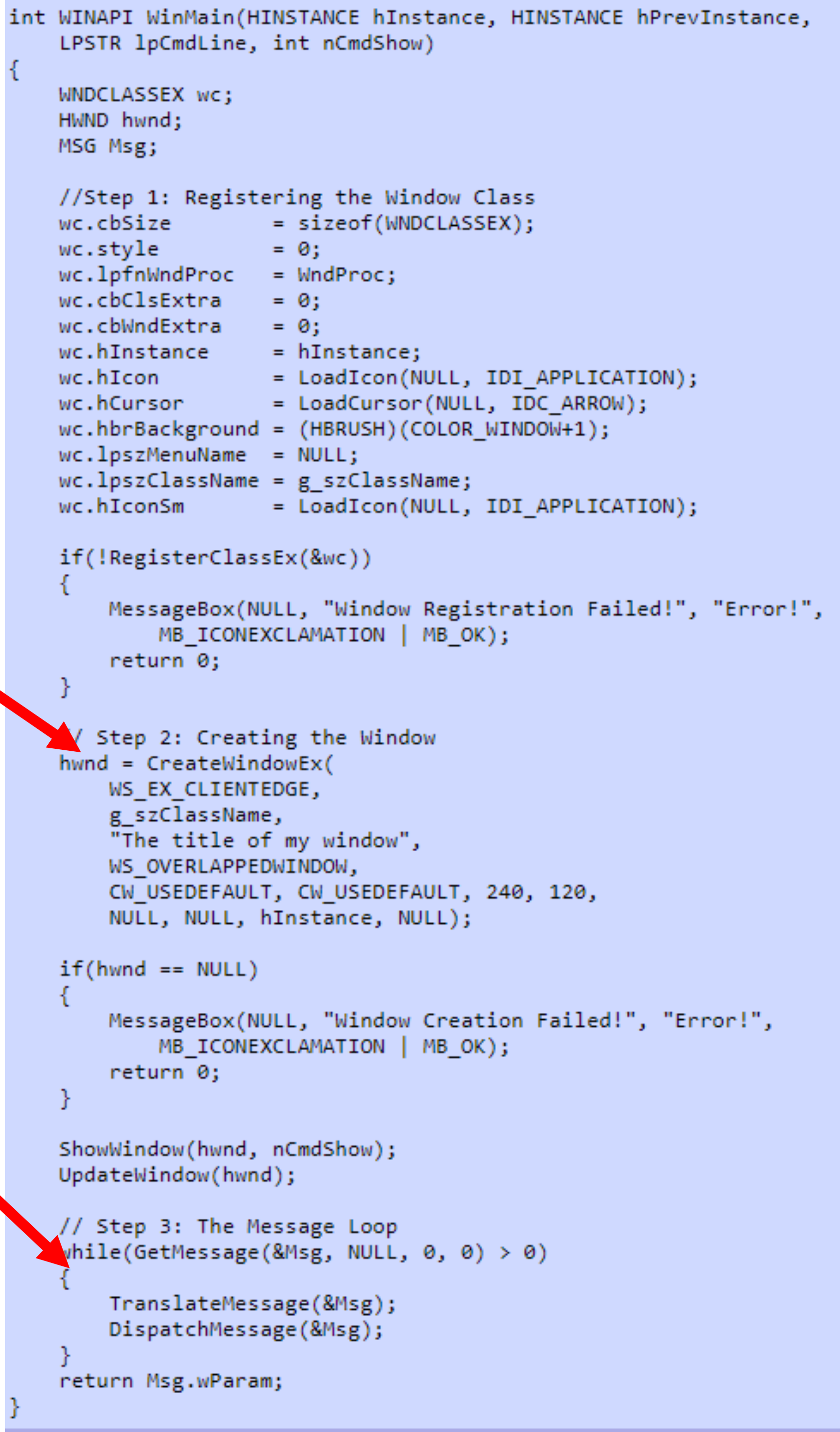

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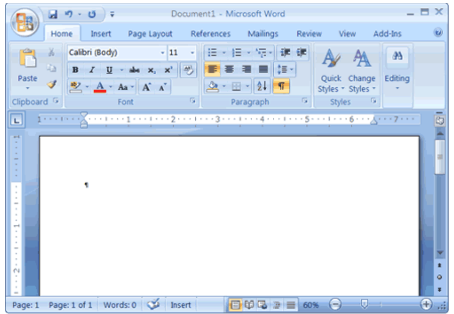

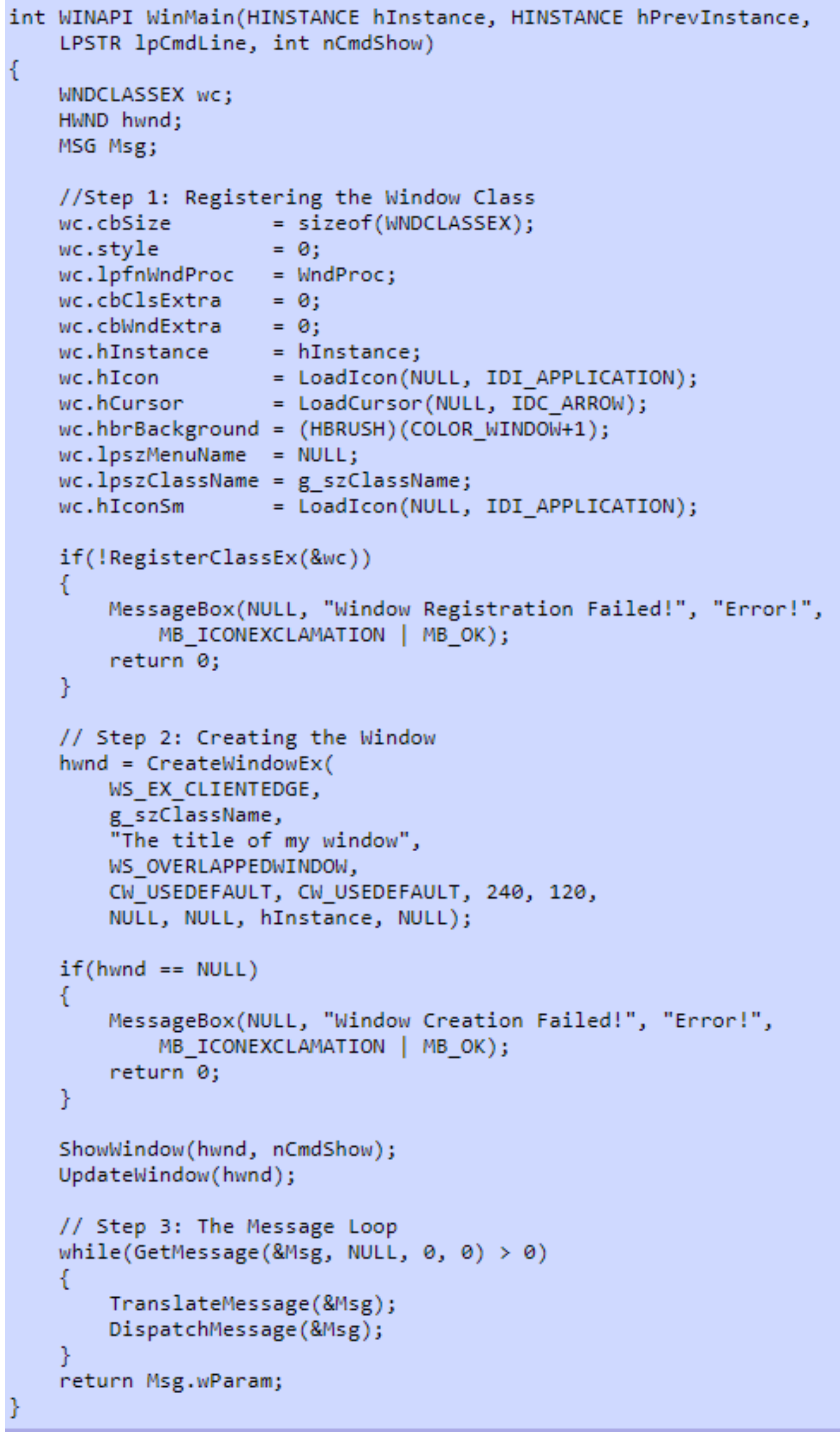

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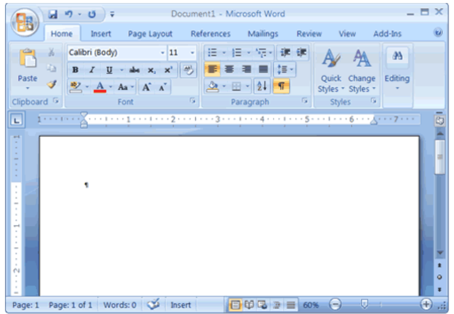

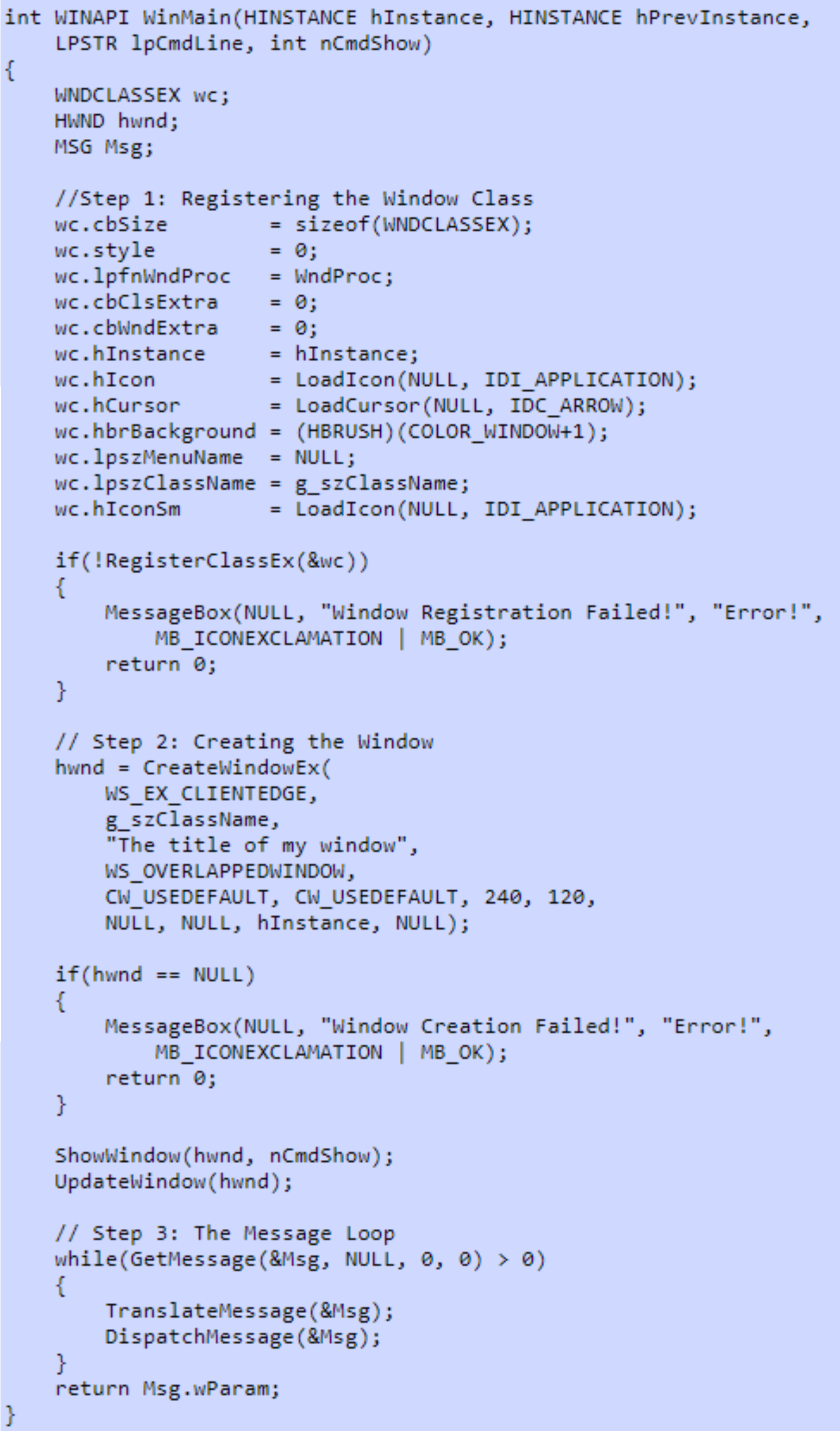

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Hex	Decimal	Symbolic
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0001	1	WM_CREATE
0002	2	WM_DESTROY
0003	3	WM_MOVE
0005	5	WM_SIZE
0006	6	WM_ACTIVATE
0007	7	WM_SETFOCUS
0008	8	WM_KILLFOCUS
000a	10	WM_ENABLE
000b	11	WM_SETREDRAW
000c	12	WM_SETTEXT
000d	13	WM_GETTEXT
000e	14	WM_GETTEXTLENGTH
000f	15	WM_PAINT
0010	16	WM_CLOSE
0011	17	WM_QUERYENDSESSION
0012	18	WM_QUIT
0013	19	WM_QUERYOPEN
0014	20	WM_ERASEBKGND

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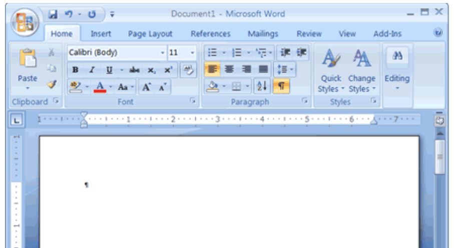

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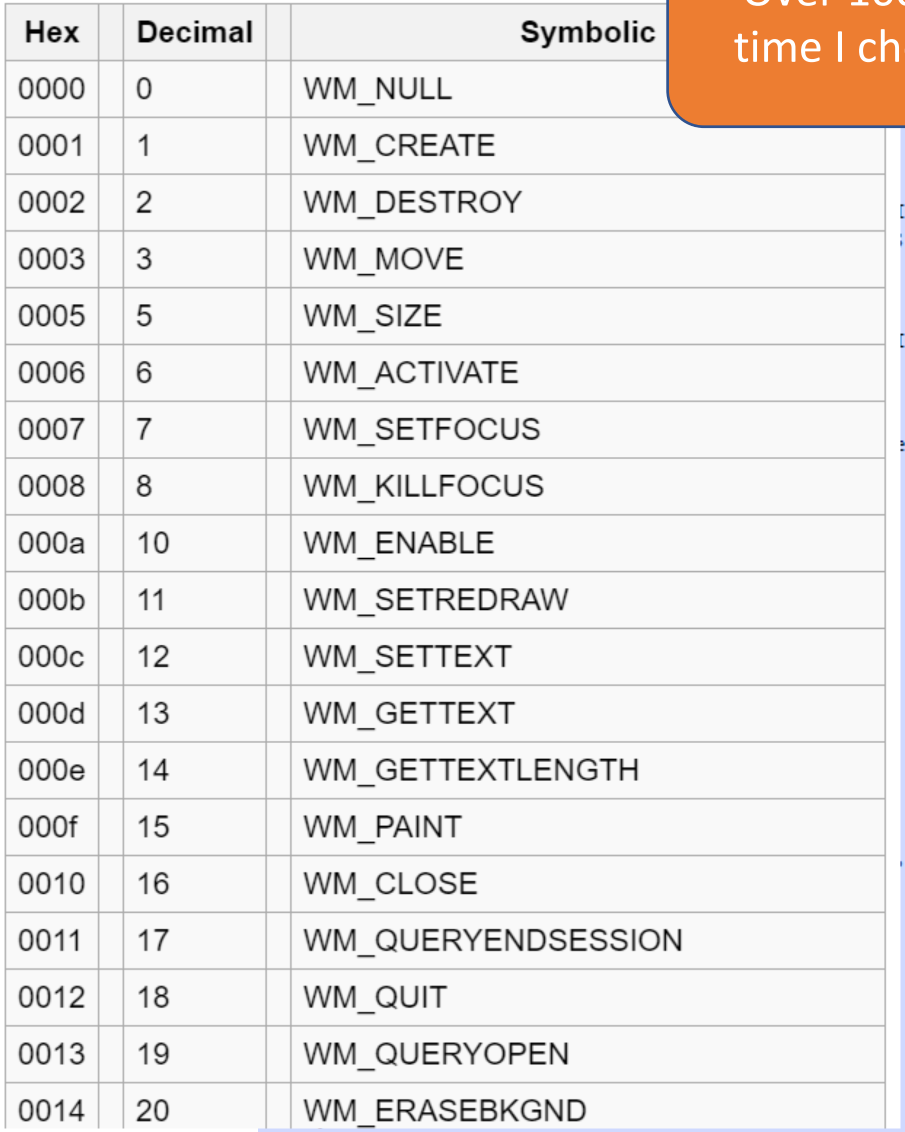

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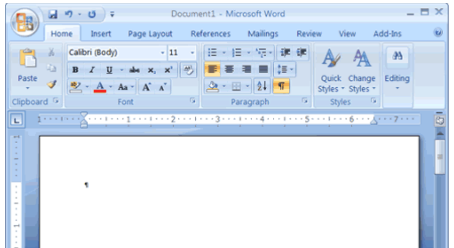
000a	10	WM_ENABLE
000b	11	WM_SETREDRAW
000c	12	WM_SETTEXT
000d	13	WM_GETTEXT
000e	14	WM_GETTEXTLENGTH
000f	15	WM_PAINT
0010	16	WM_CLOSE
0011	17	WM_QUERYENDSESSION
0012	18	WM_QUIT
0013	19	WM_QUERYOPEN
0014	20	WM_ERASEBKGND

Over 1000 last time I checked!

```
int WINAPI WinMain(HINSTANCE hInstance, HINSTANCE hPrevInstance,
    LPSTR lpCmdLine, int nCmdShow)
{
    WNDCLASSEX wc;
    HWND hwnd;
    MSG Msg;
```

```
ION);
;
ION);
ed!", "Error!",
, "Error!",
```

```
        TranslateMessage(&Msg);
        DispatchMessage(&Msg);
    }
    return Msg.wParam;
}
```



GUI programming

```
switch (message)
{
        //case WM_COMMAND:
          // handle menu select
        //break;
        //case WM_PAINT:
          // draw our window -                      r not
        //break;
        case WM_DESTROY:
             PostQuitMessage(0);
        break;
        default:
            // We do not want to handle this message so pass back to Winc
            // to handle it in a default way
            return DefWindowProc(hWnd, message, wParam, lParam);
}
```

```
void OnMove() { … }
void OnSize() { … }


void OnPaint() { … }
```

Hex	Decimal	Symbolic
0000	0	WM_NULL
0001	1	WM_CREATE
0002	2	WM_DESTROY
0003	3	WM_MOVE
0005	5	WM_SIZE
0006	6	WM_ACTIVATE
0007	7	WM_SETFOCUS
0008	8	WM_KILLFOCUS
000a	10	WM_ENABLE
000b	11	WM_SETREDRAW
000c	12	WM_SETTEXT
000d	13	WM_GETTEXT
000e	14	WM_GETTEXTLENGTH
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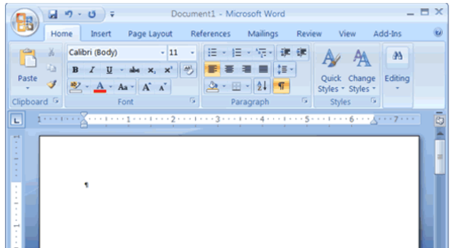
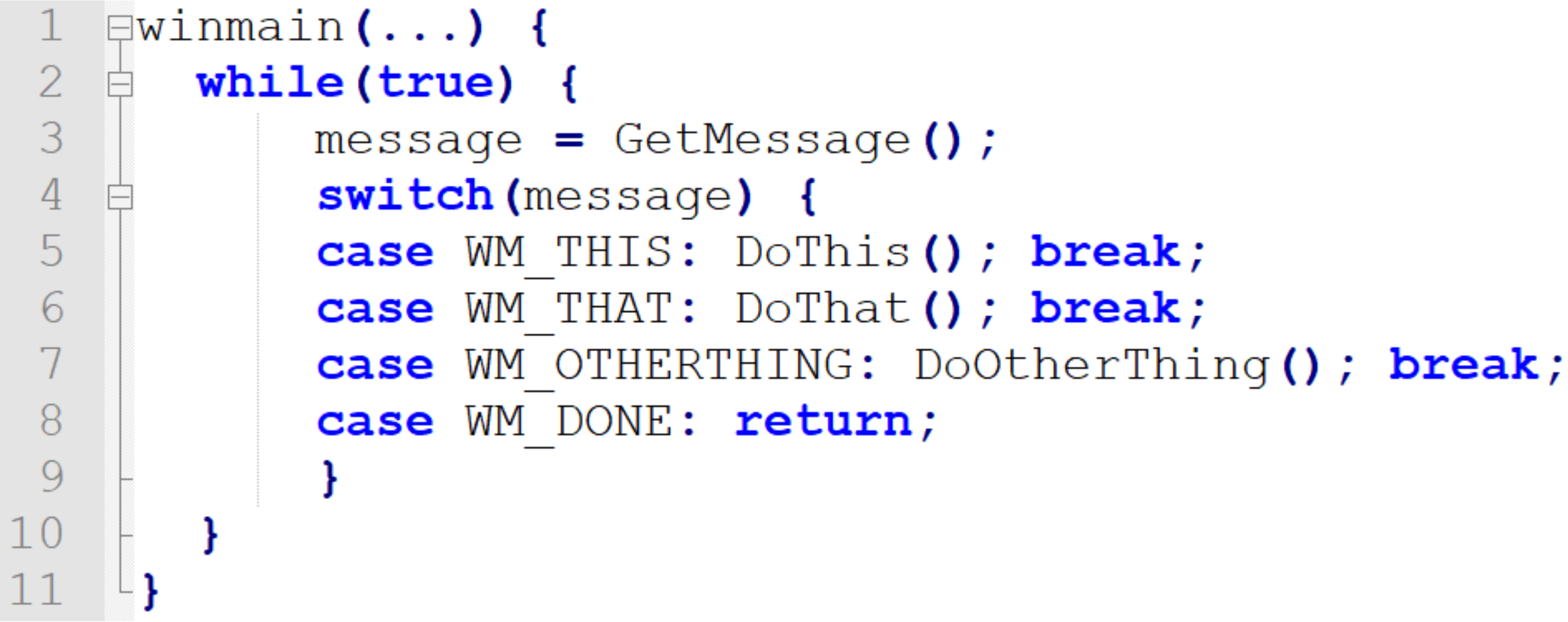


GUI Programming Distilled



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      message = GetMessage();
      switch(message) {
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      case WM_DONE: return;
      }
  }
}
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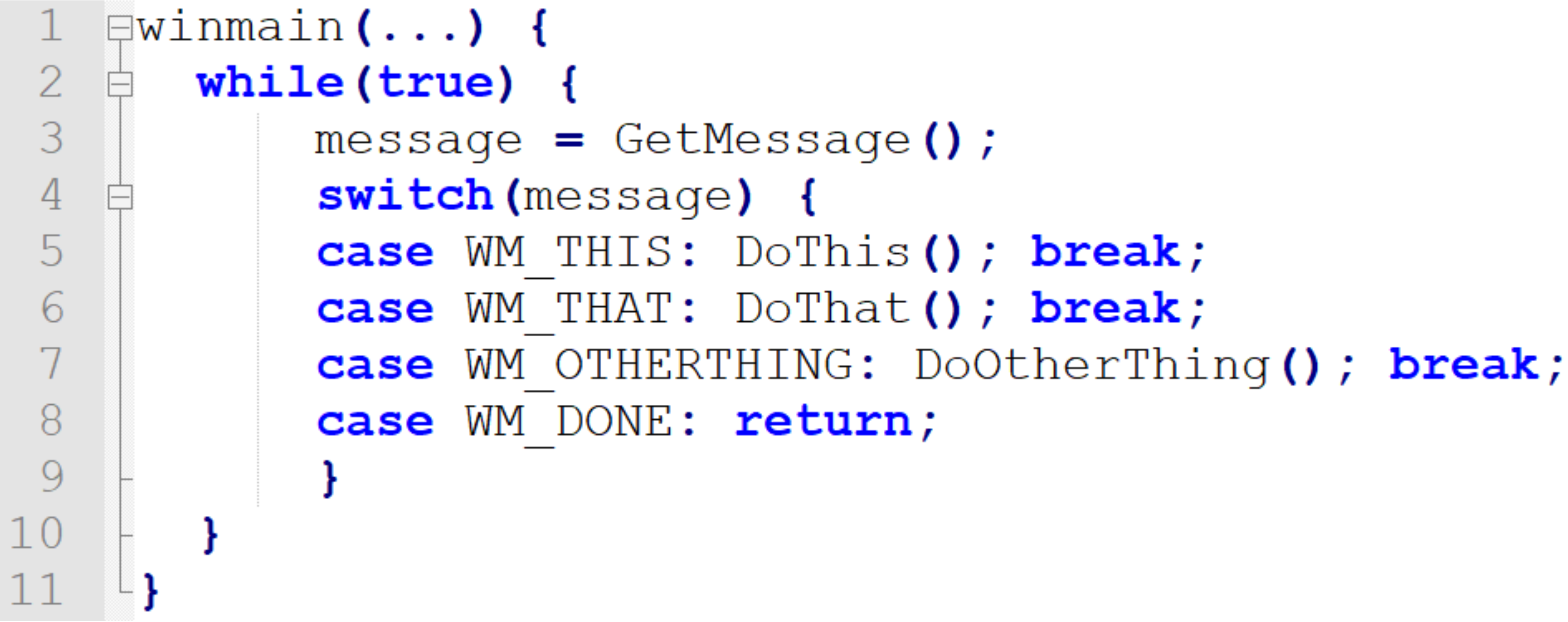
GUI Programming Distilled



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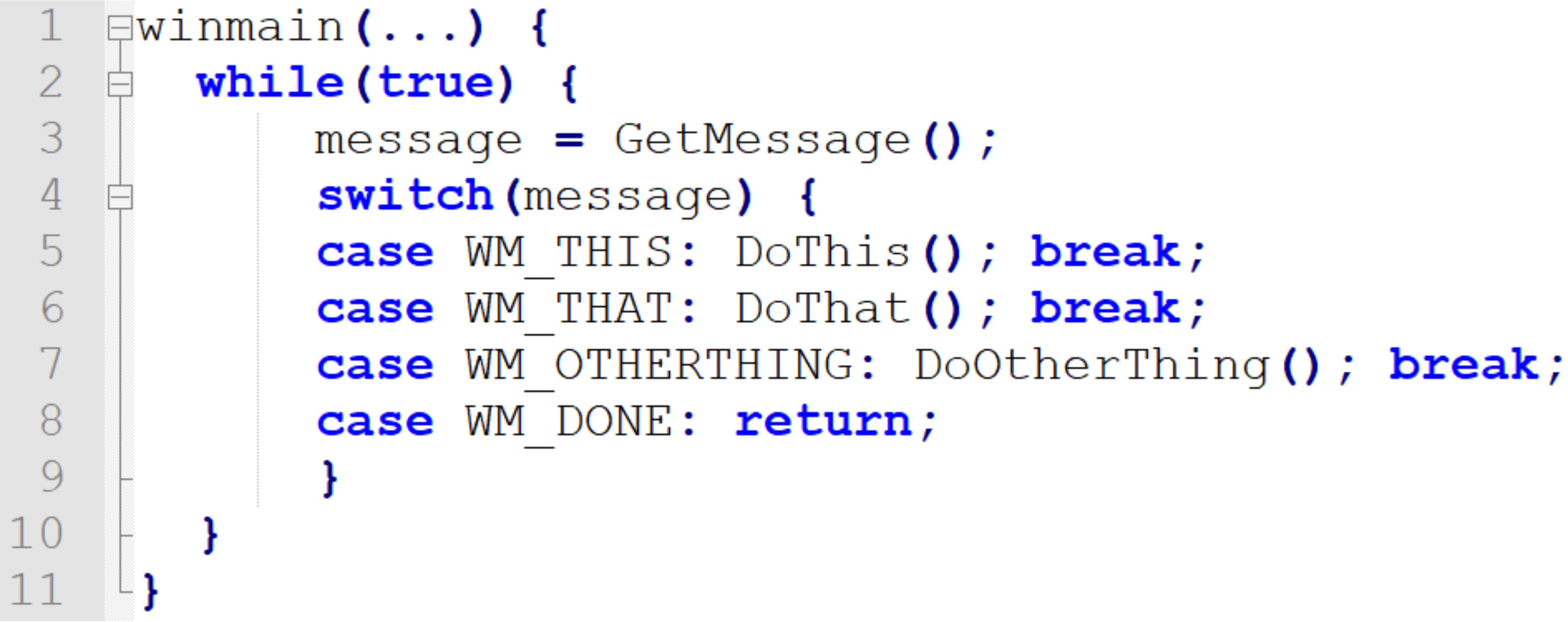
Pros

GUI Programming Distilled



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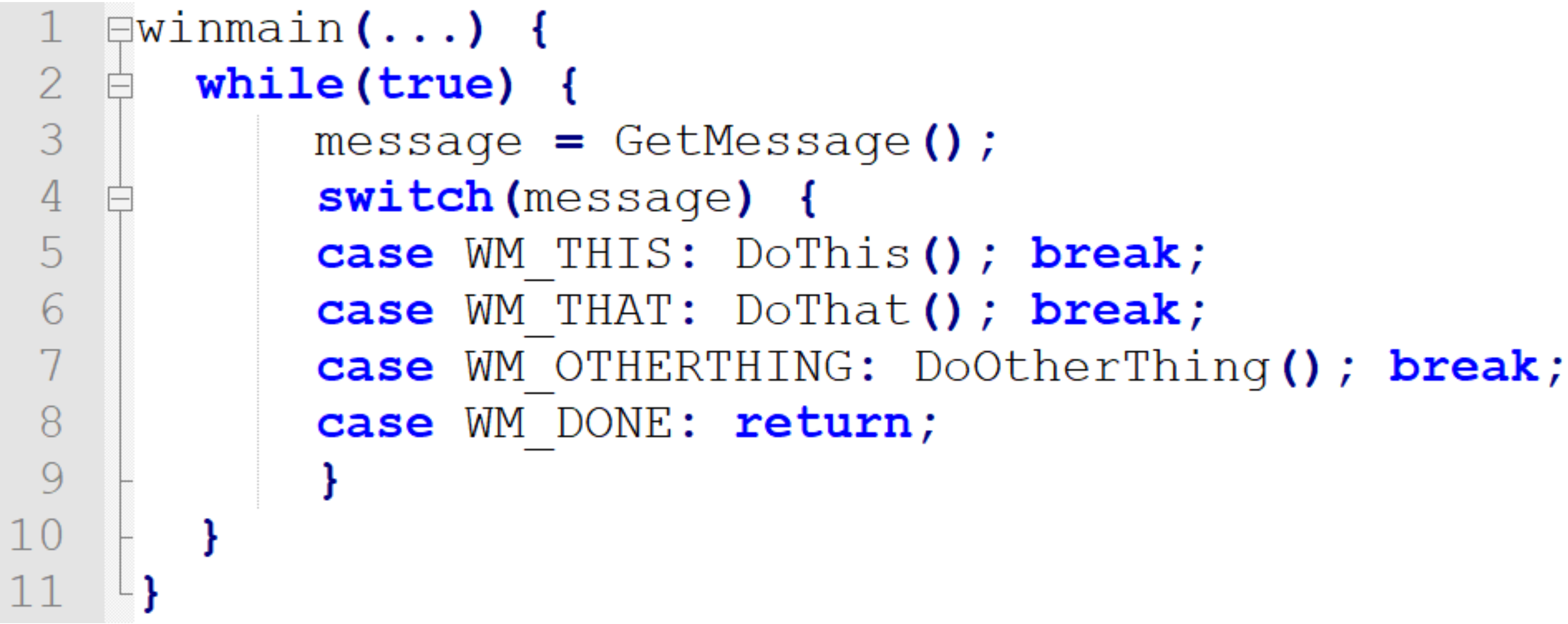
Pros

- Simple imperative programming

GUI Programming Distilled



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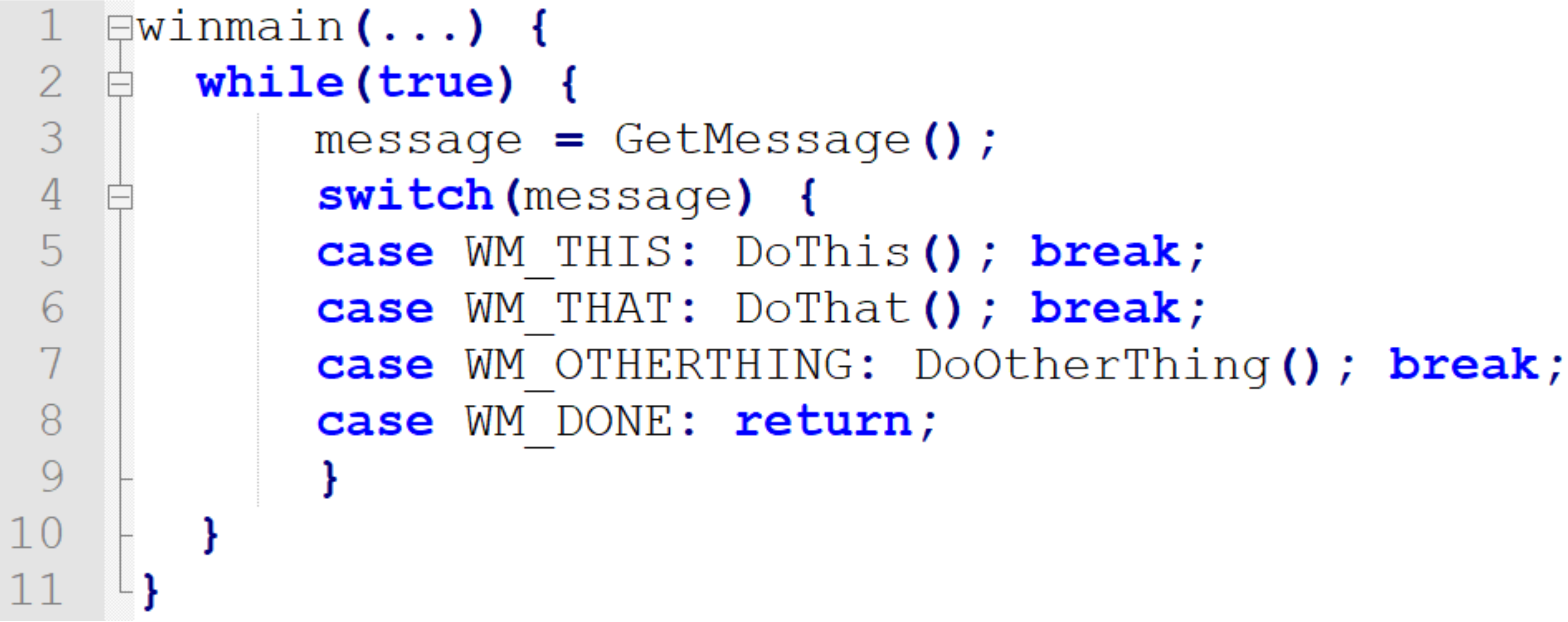
Pros

- Simple imperative programming
- Good fit for uni-processor

GUI Programming Distilled



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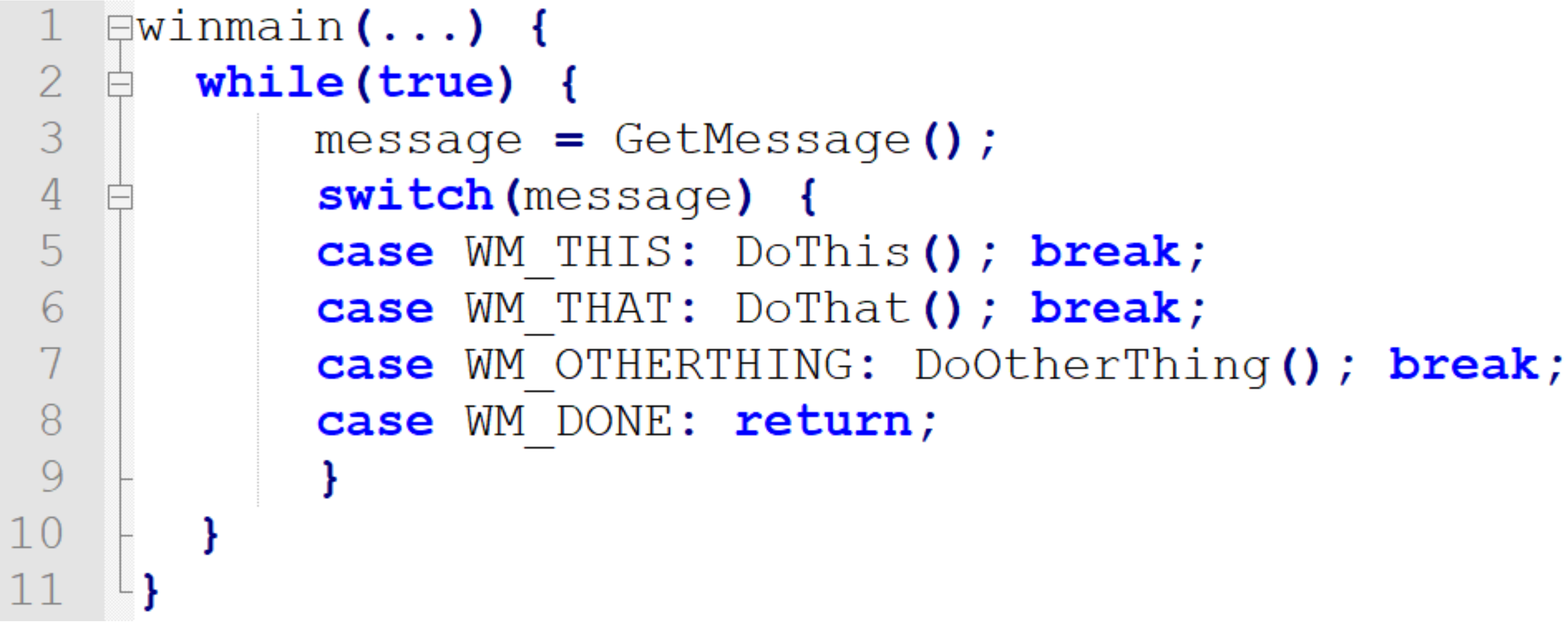
Cons

GUI Programming Distilled



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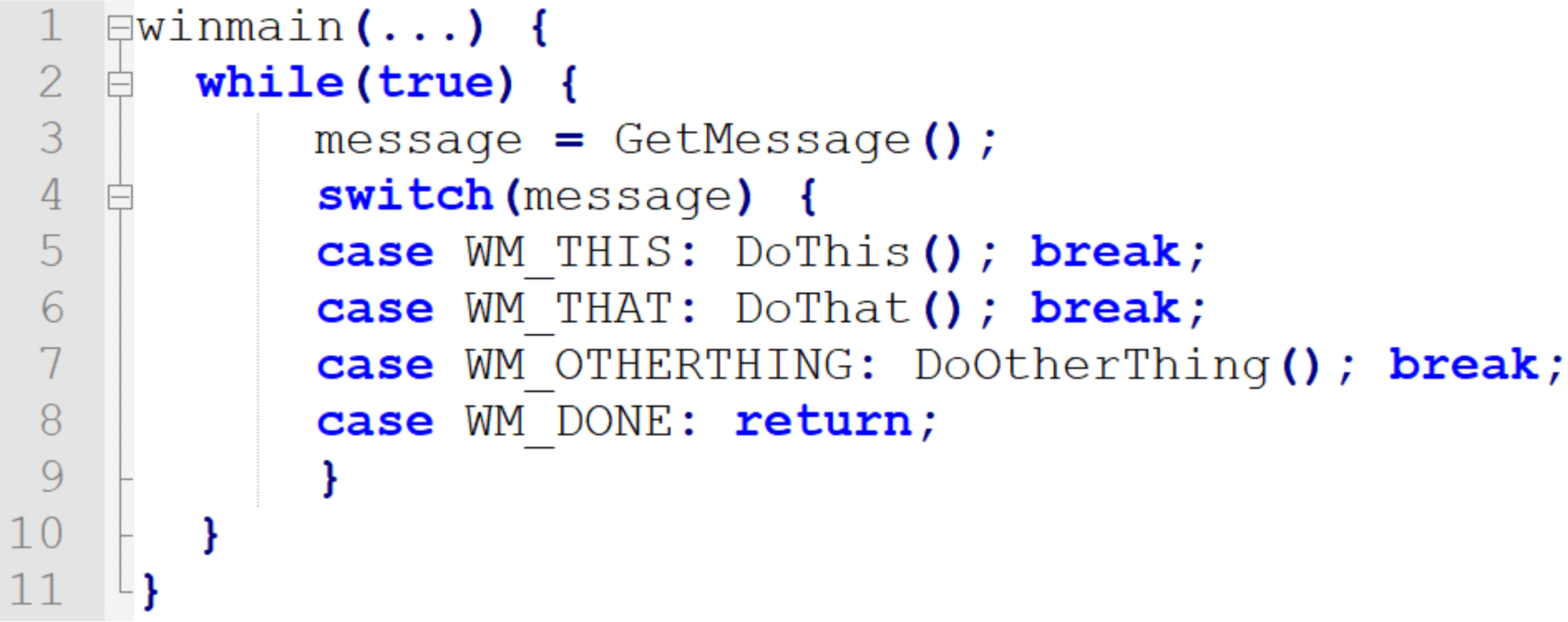
Pros

- Simple imperative programming
- Good fit for uni-processor

Cons

- Awkward/verbose

GUI Programming Distilled



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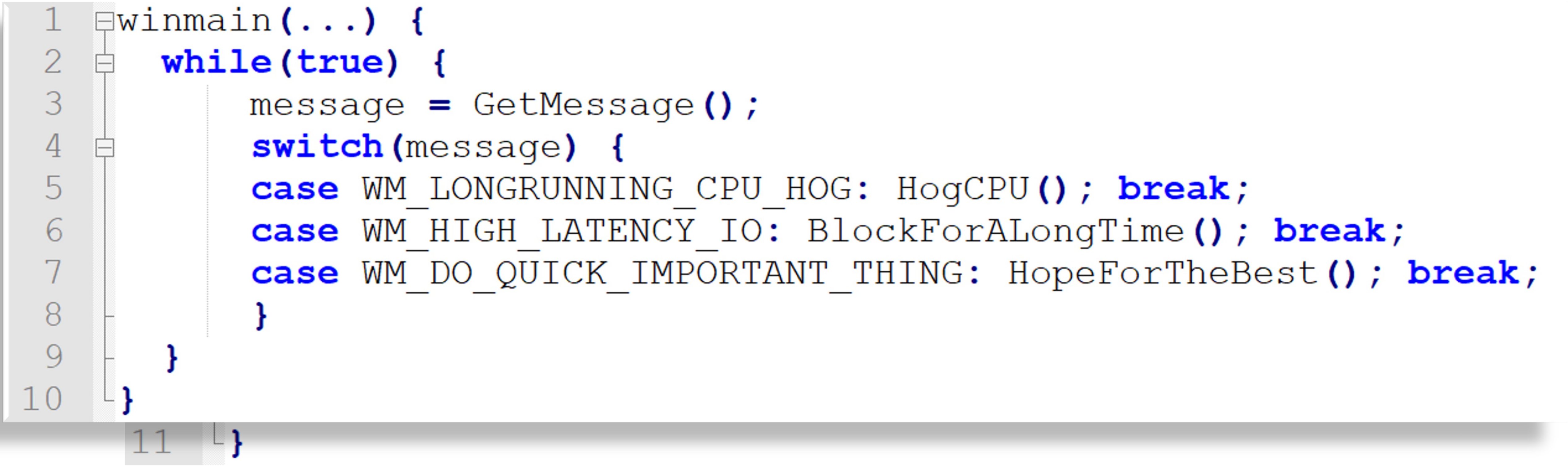
Pros

- Simple imperative programming
- Good fit for uni-processor

Cons

- Awkward/verbose
- **Obscures available parallelism**

GUI Programming Distilled



```
winmain(...) {
  while(true) {
      message = GetMessage();
      switch(message) {
      case WM_LONGRUNNING_CPU_HOG: HogCPU(); break;
      case WM_HIGH_LATENCY_IO: BlockForALongTime(); break;
      case WM_DO_QUICK_IMPORTANT_THING: HopeForTheBest(); break;
      }
  }
}
}
```

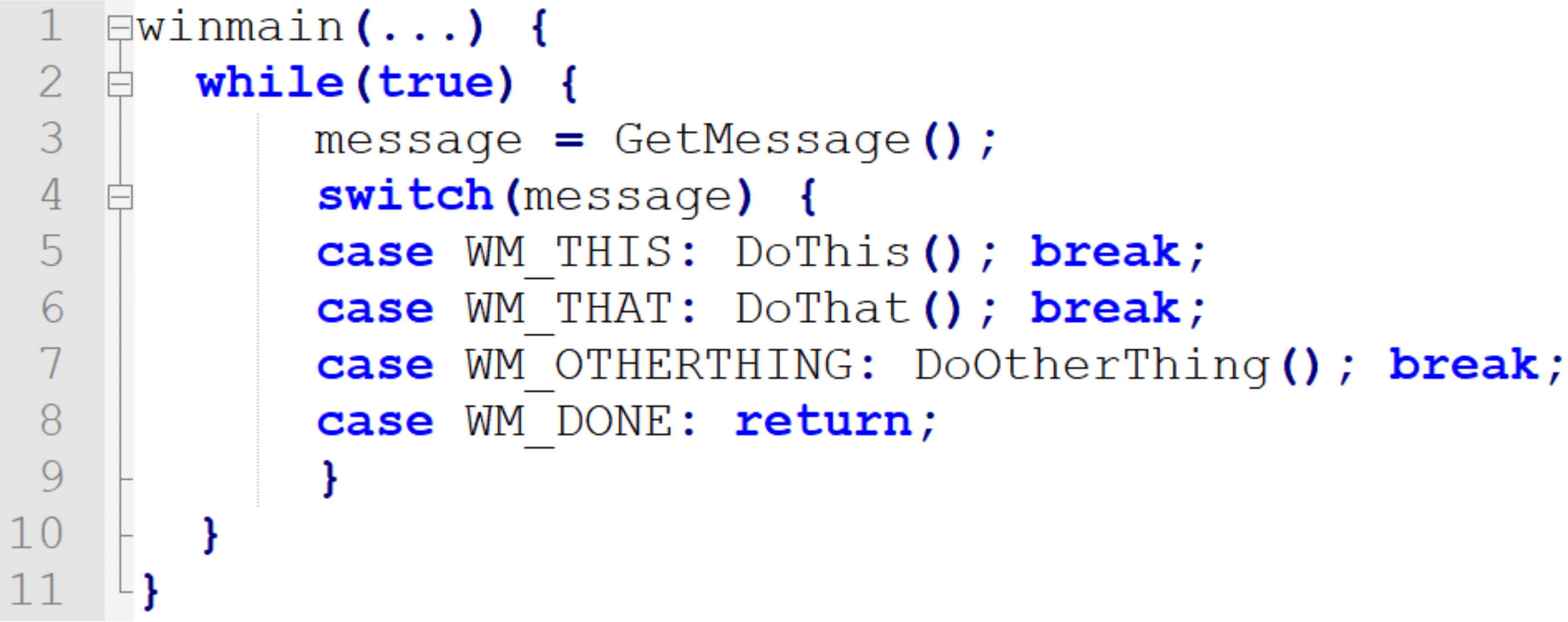
Pros

- Simple imperative programming
- Good fit for uni-processor

Cons

- Awkward/verbose
- **Obscures available parallelism**

GUI Programming Distilled



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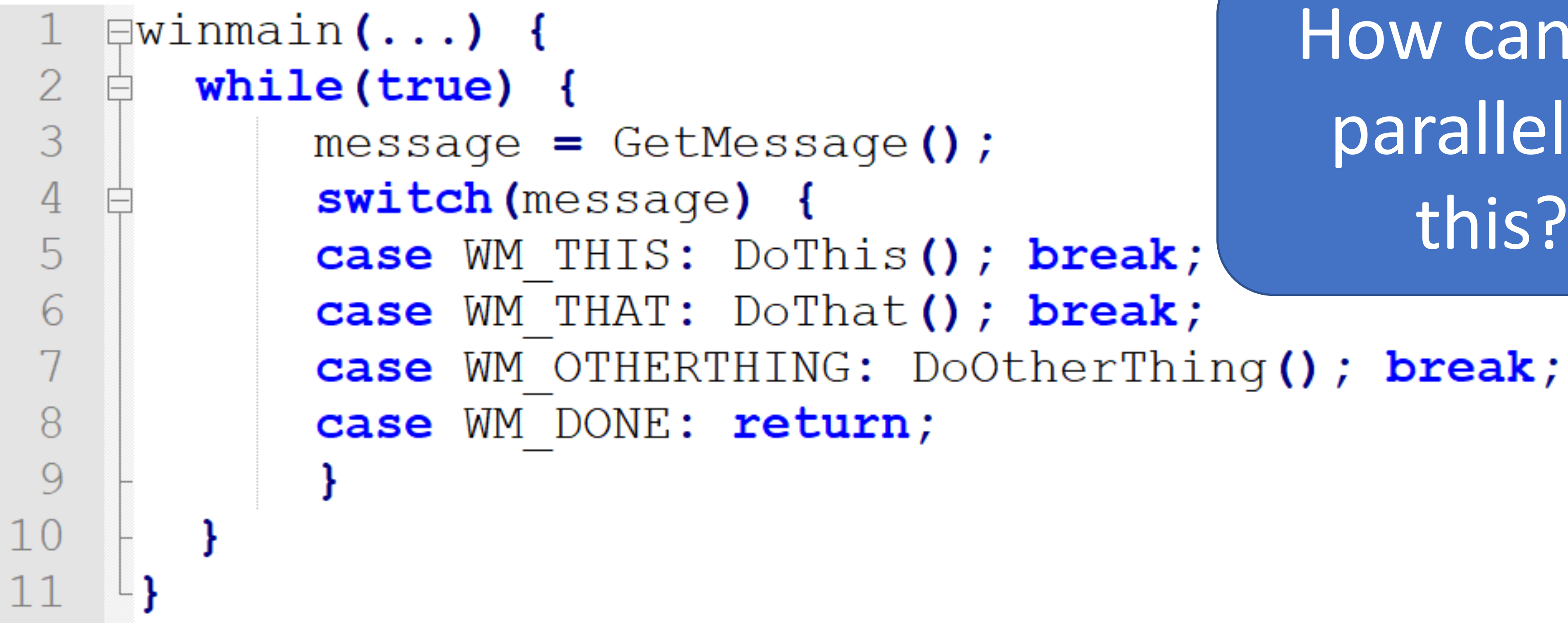

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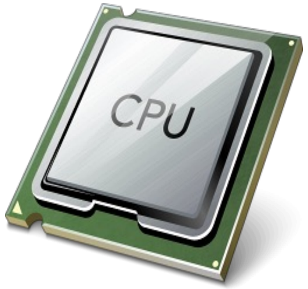
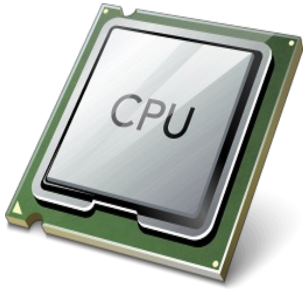
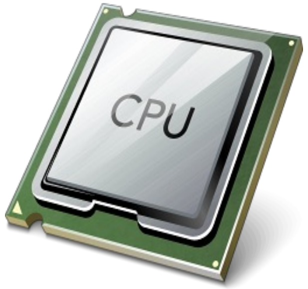
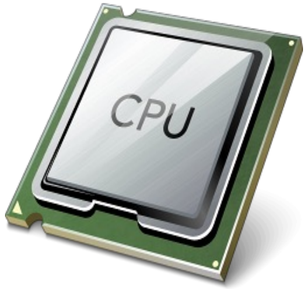
```

How can we parallelize this?

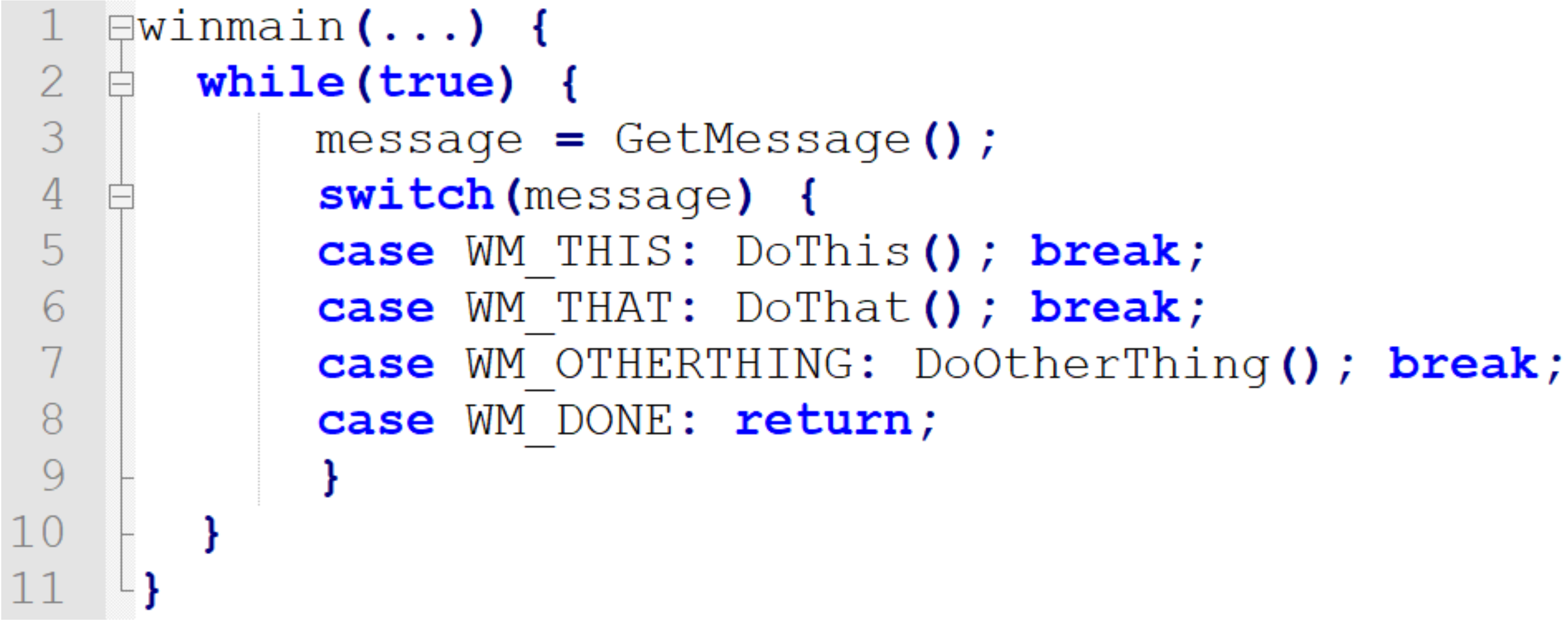








Parallel GUI Implementation 1



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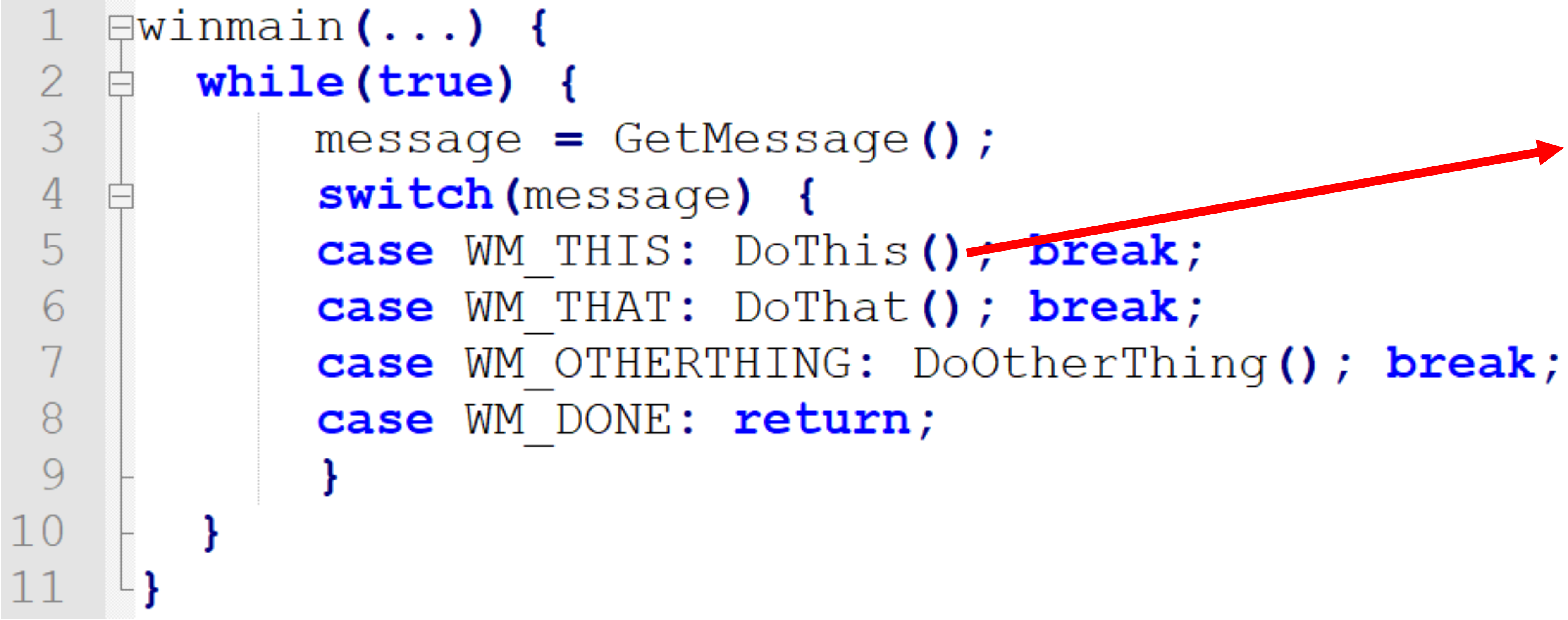

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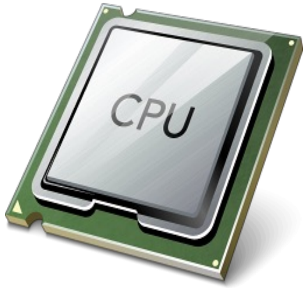

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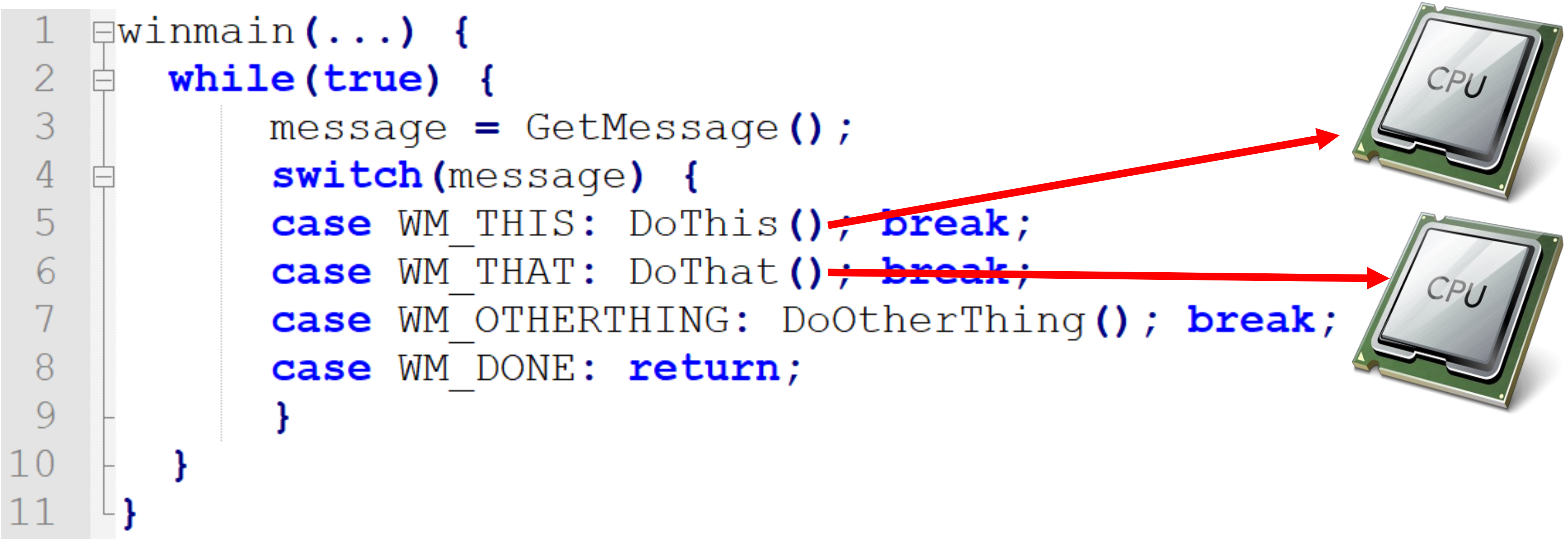

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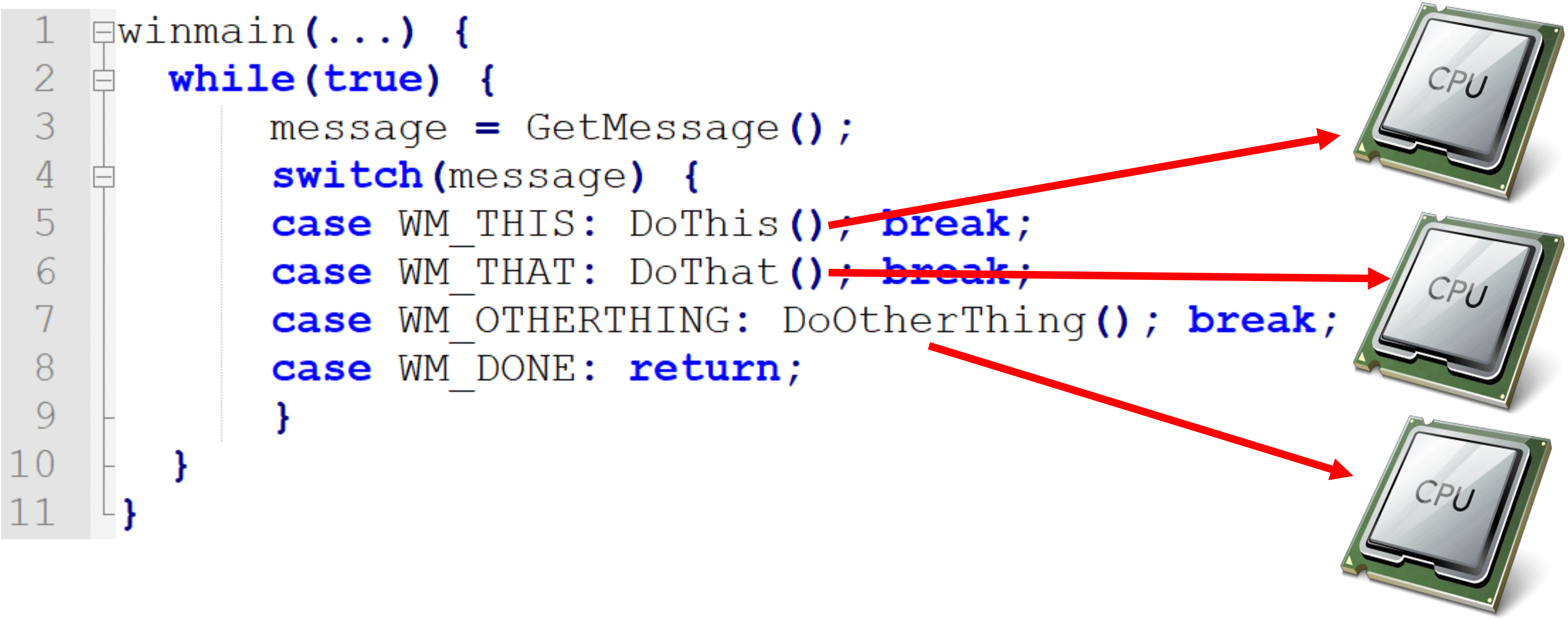

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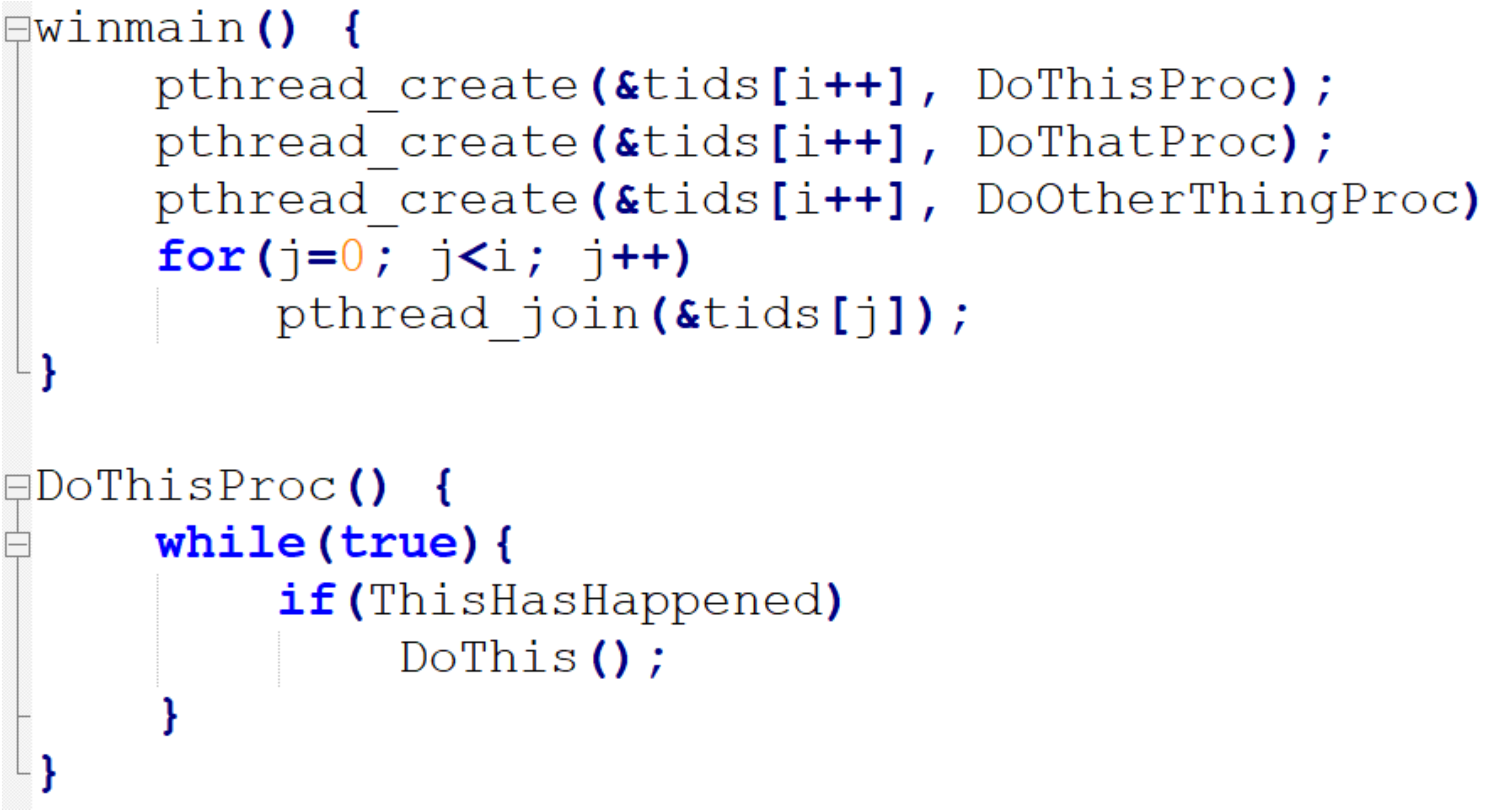
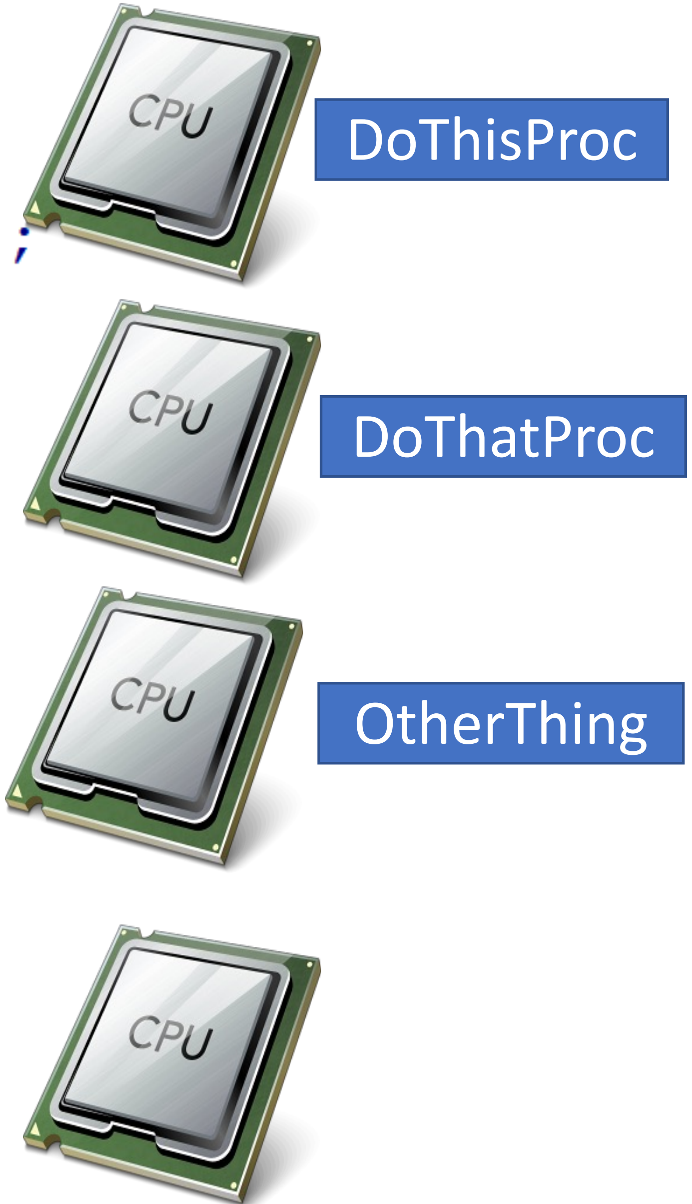
Parallel GUI Implementation 1



```
winmain() {
    pthread_create(&tids[i++], DoThisProc);
    pthread_create(&tids[i++], DoThatProc);
    pthread_create(&tids[i++], DoOtherThingProc);
    for(j=0; j<i; j++)
        pthread_join(&tids[j]);
}

DoThisProc() {
    while(true){
        if(ThisHasHappened)
            DoThis();
    }
}
```

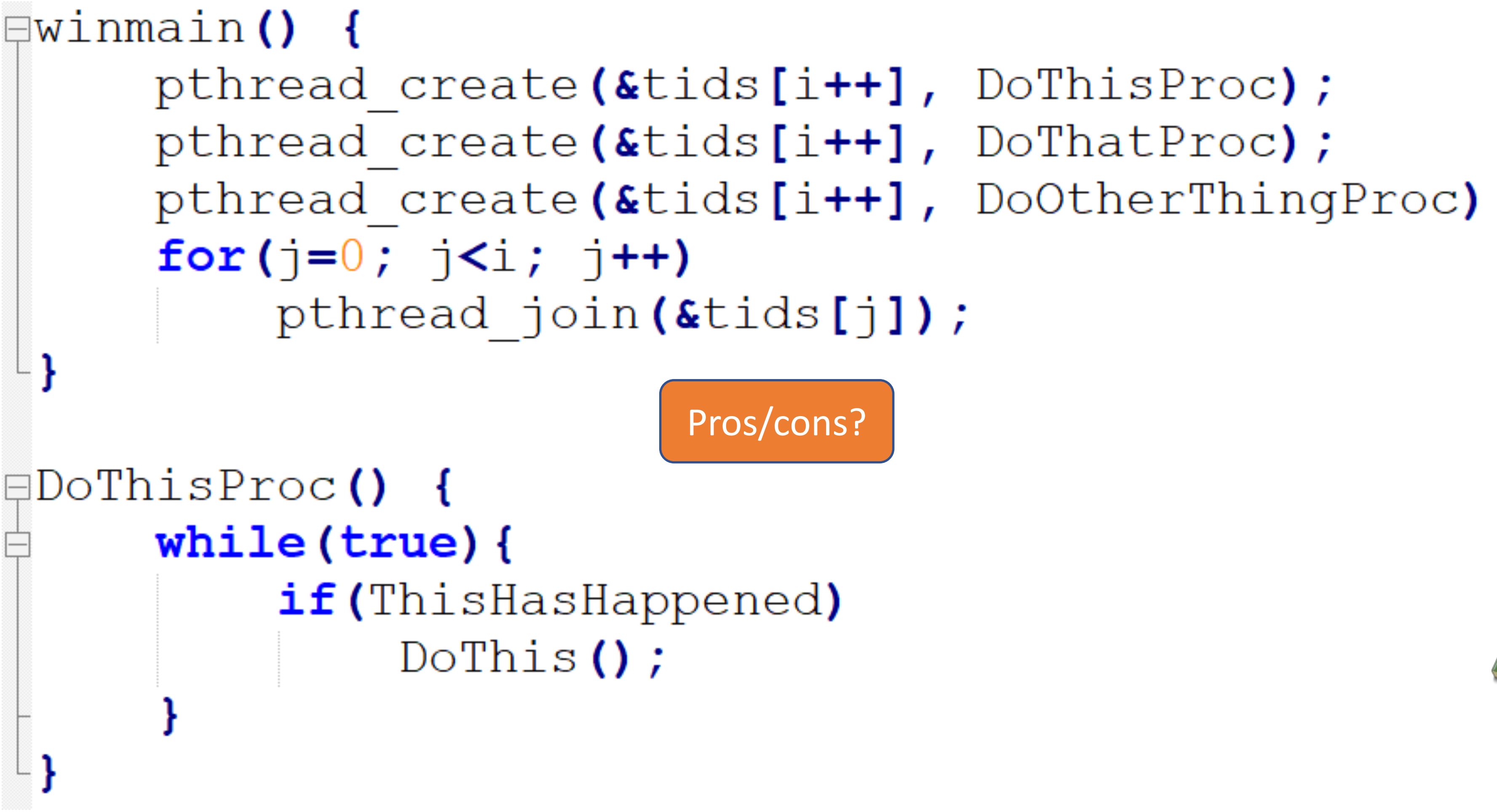


DoThisProc

DoThatProc

OtherThing

Parallel GUI Implementation 1



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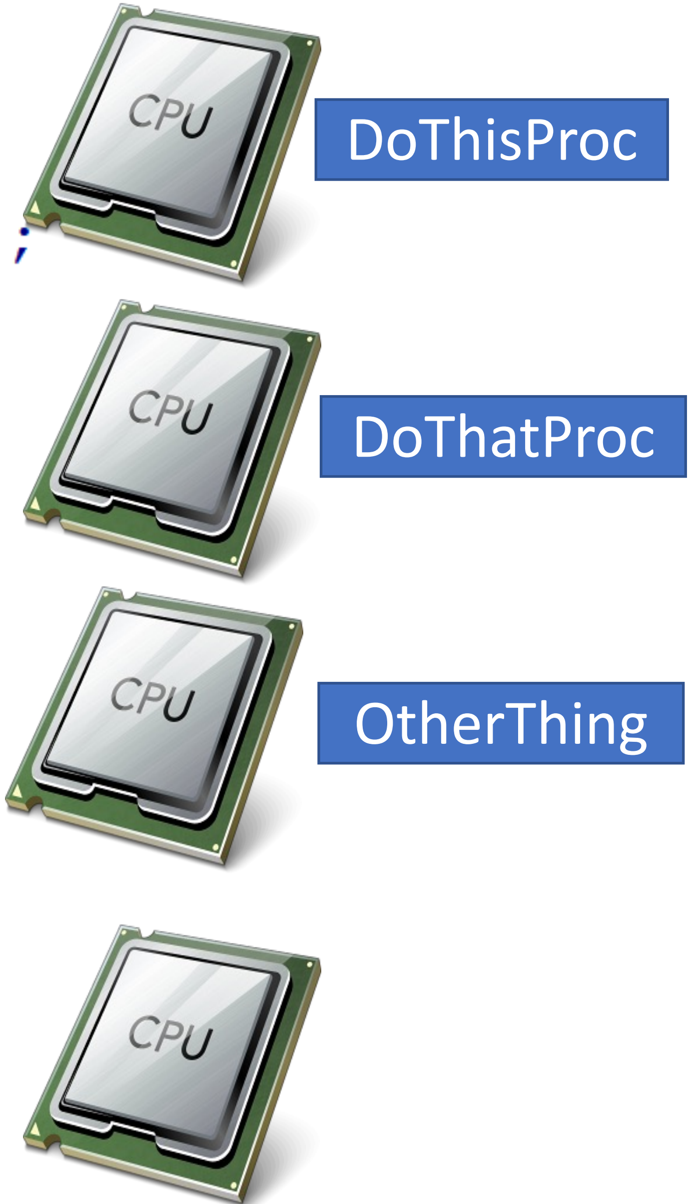
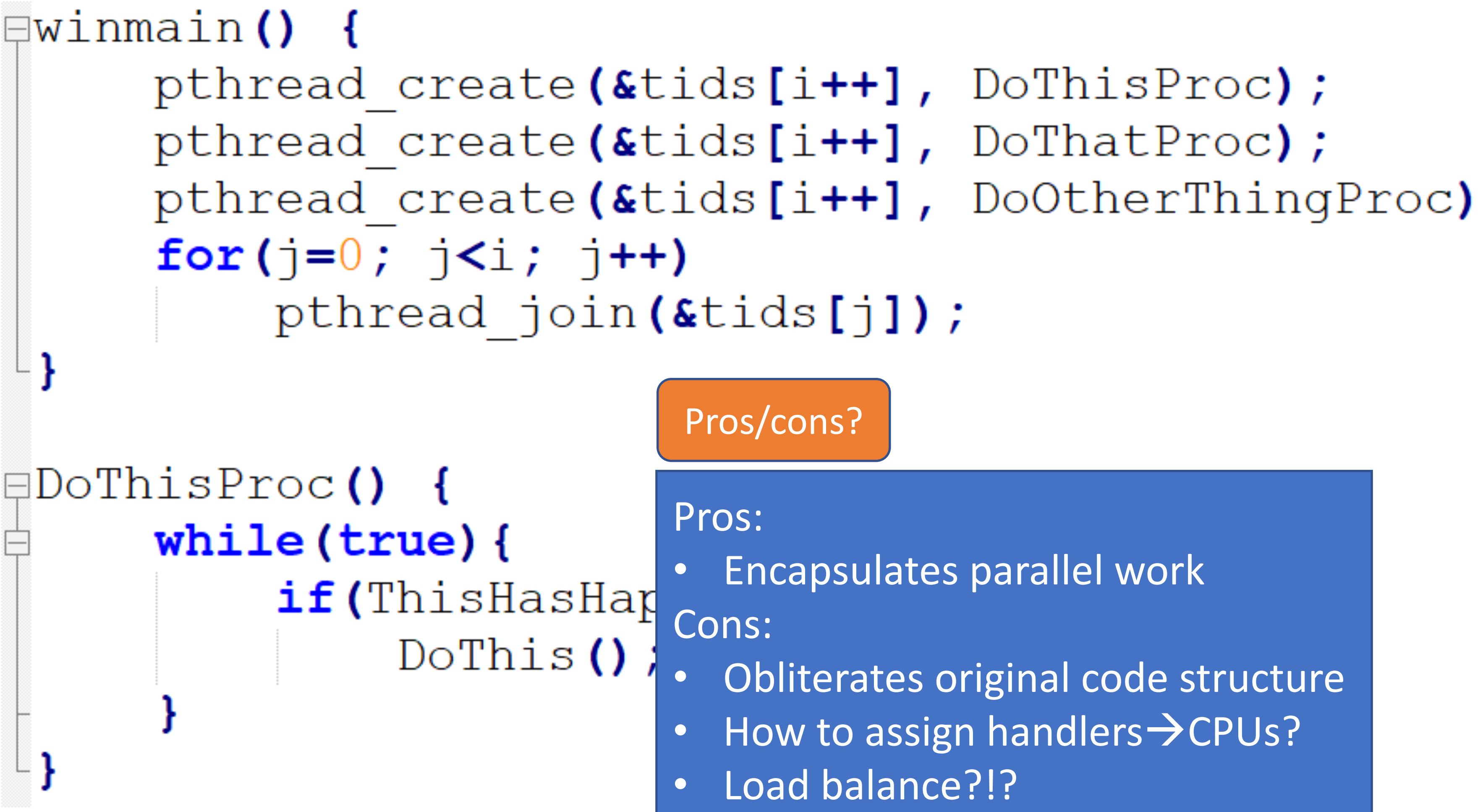
Pros/cons?



Parallel GUI Implementation 1



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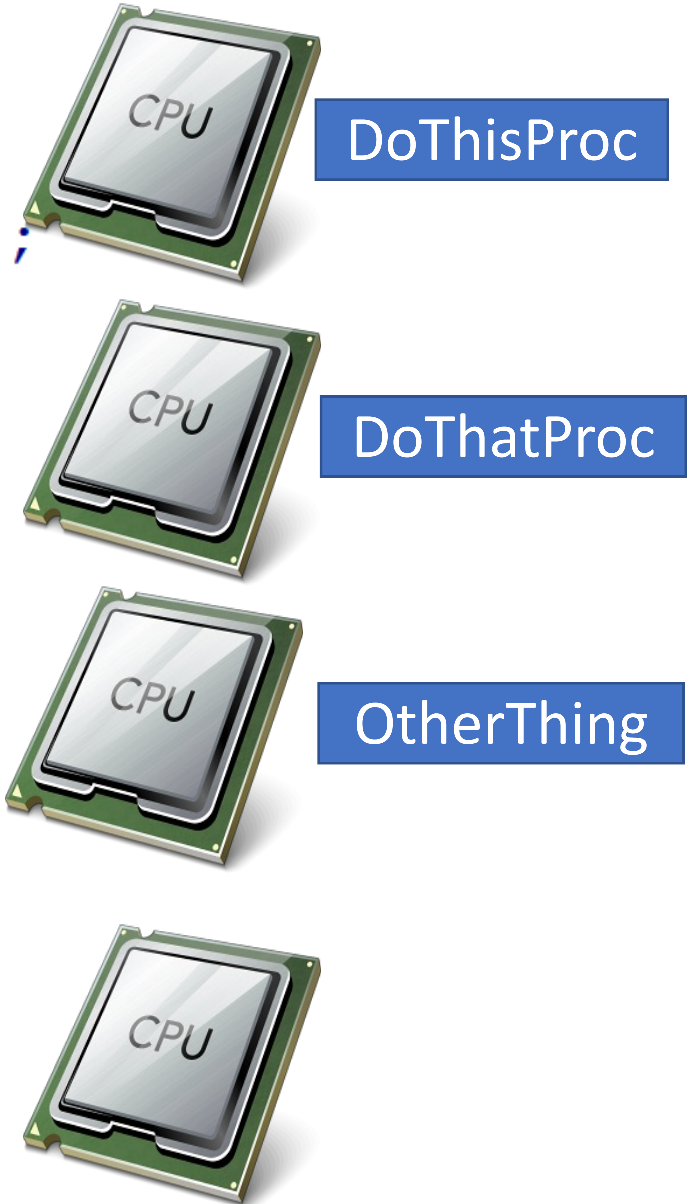
        pthread_join(&tids[j]);
}

DoThisProc() {
    while(true){
        if(ThisHasHap
            DoThis();
    }
}
```

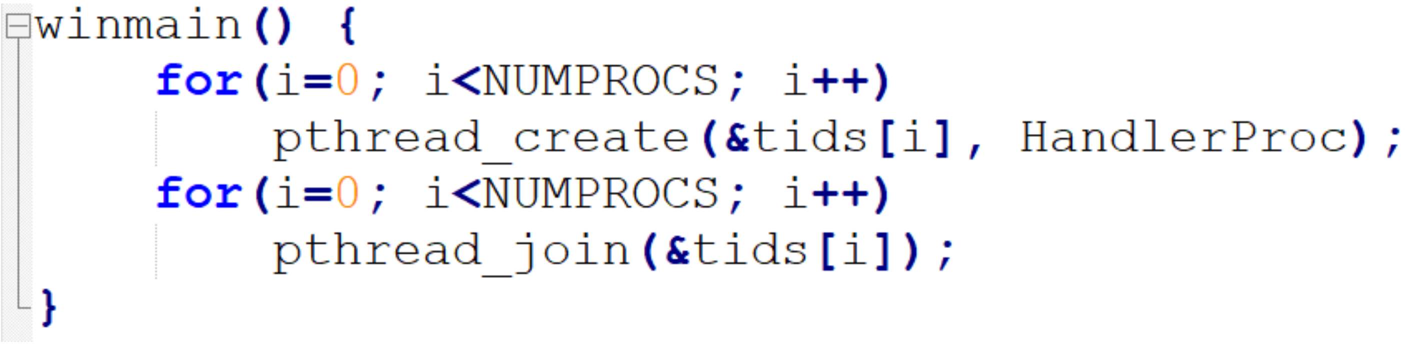
Pros/cons?

Pros:
- Encapsulates parallel work

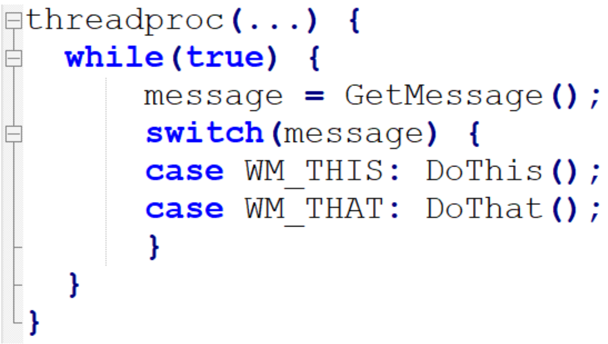
Cons:
- Obliterates original code structure
- How to assign handlers→CPUs?
- Load balance?!?
- Utilization



Parallel GUI Implementation 2



```
winmain() {
        for(i=0; i<NUMPROCS; i++)
            pthread_create(&tids[i], HandlerProc);
        for(i=0; i<NUMPROCS; i++)
            pthread_join(&tids[i]);
}
```



```
threadproc(...) {
  while(true) {
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      switch(message) {
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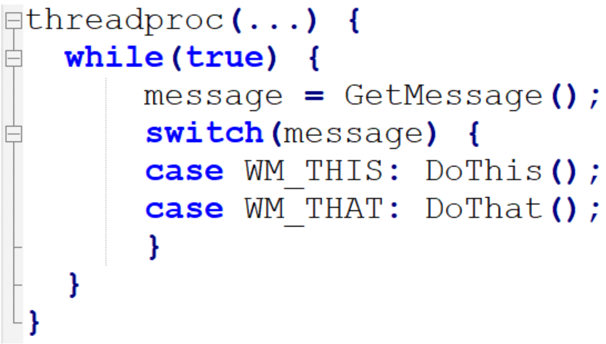
      }
  }
}
```



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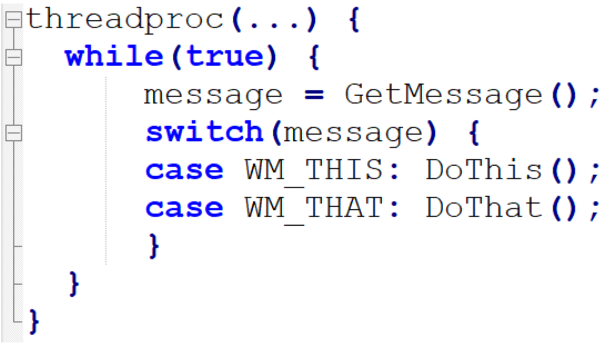

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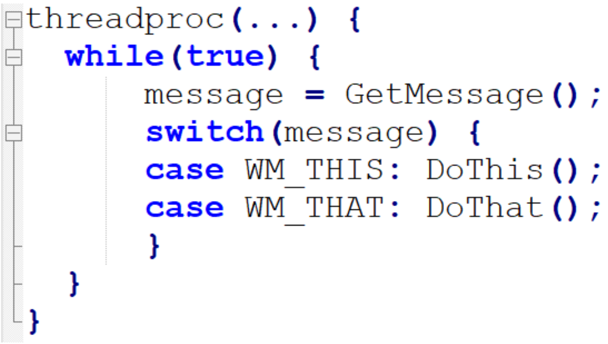

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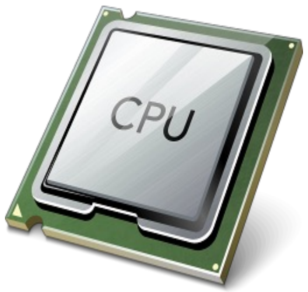
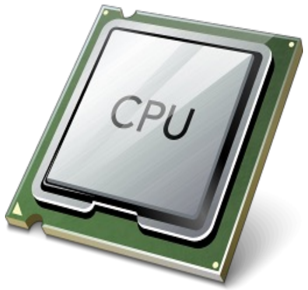
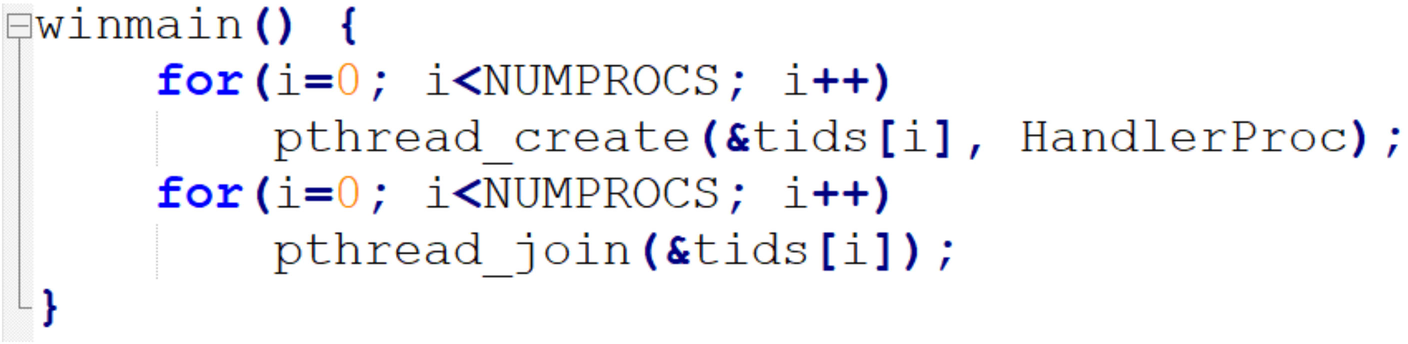




Parallel GUI Implementation 2

Pros/cons?



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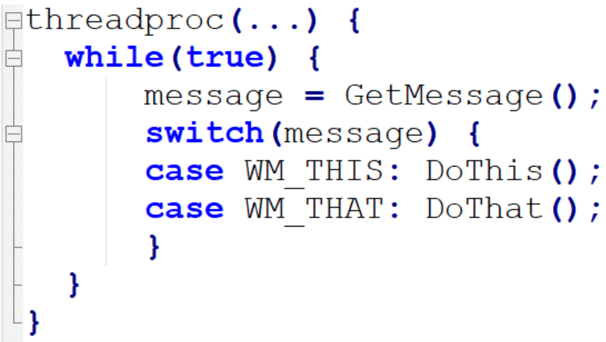

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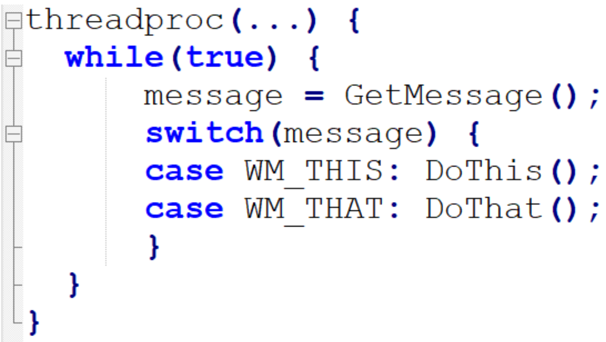

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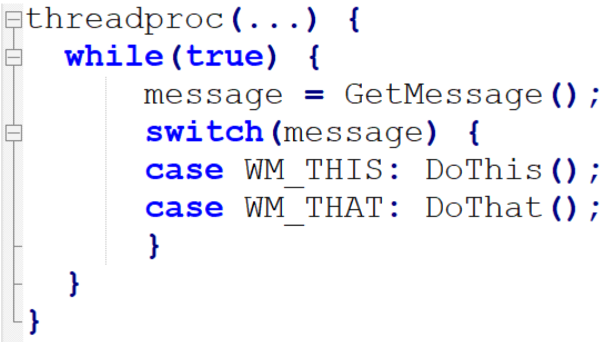

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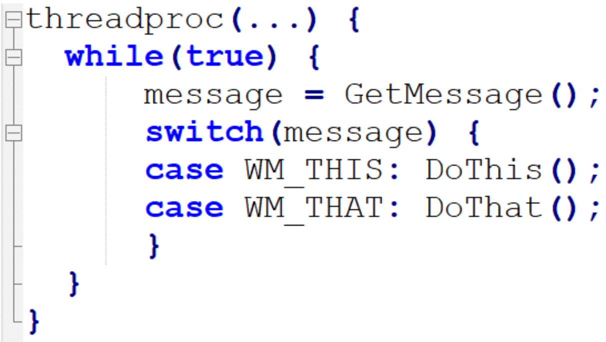

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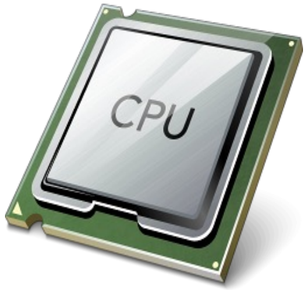
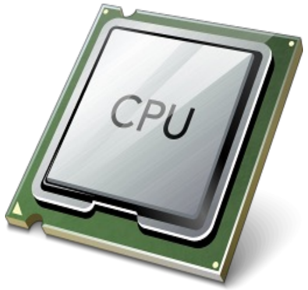
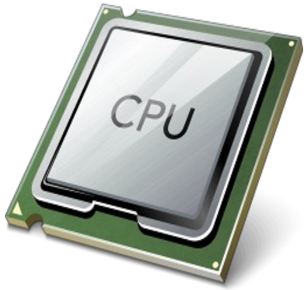
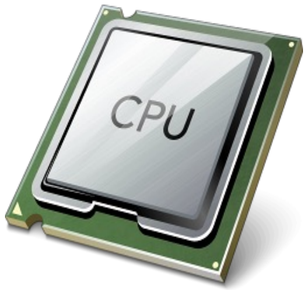
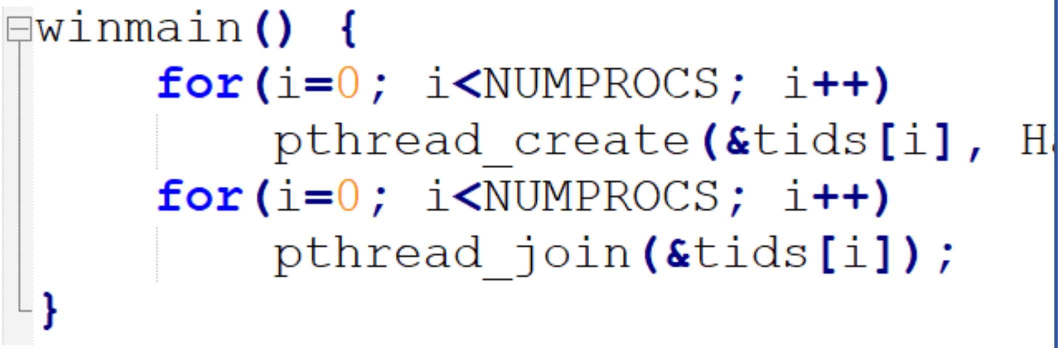








Parallel GUI Implementation 2

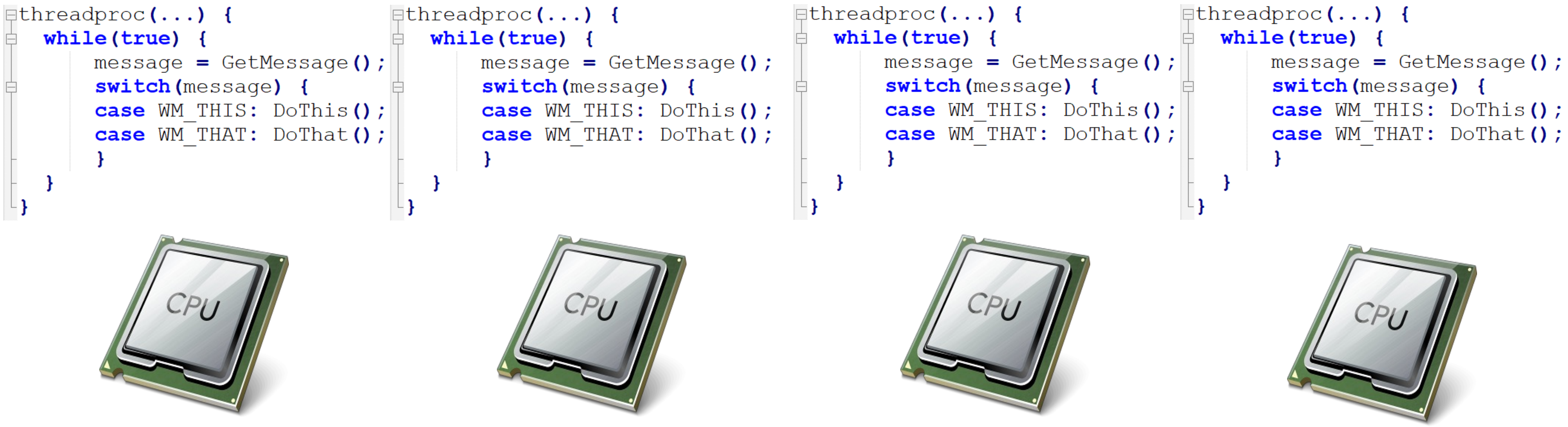


```
winmain() {
    for(i=0; i<NUMPROCS; i++)
        pthread_create(&tids[i], H
    for(i=0; i<NUMPROCS; i++)
        pthread_join(&tids[i]);
}
```

Pros/cons?

Pros:
- Preserves programming model
- Can recover some parallelism

Cons:
- Workers still have same problem
- How to load balance?
- Shared mutable state a problem



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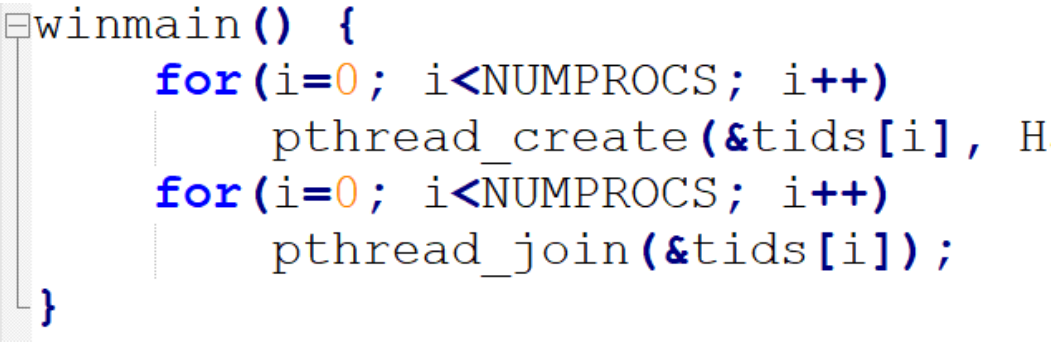

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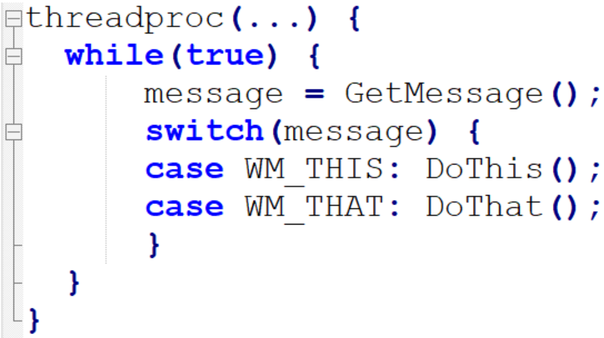

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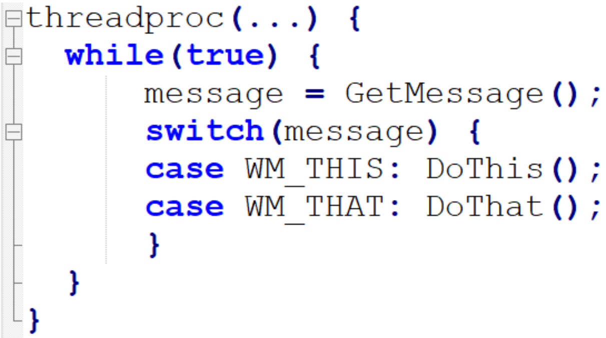

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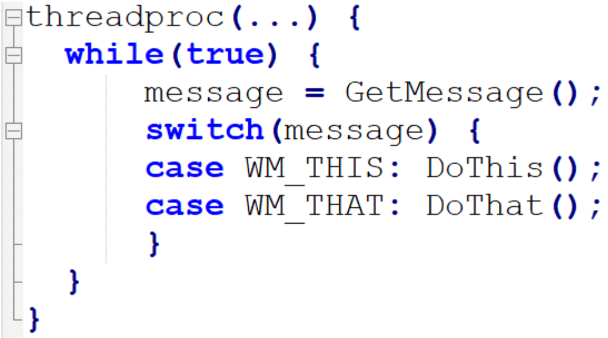

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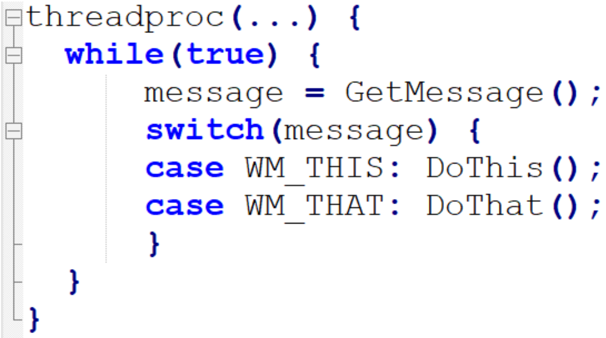

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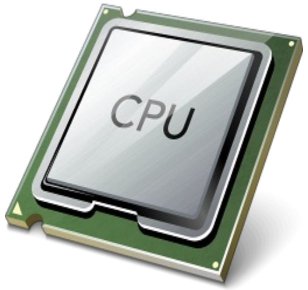

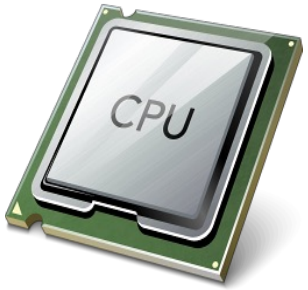

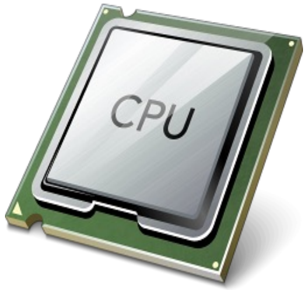

Extremely difficult to solve without changing the whole programming model…so ***change it***

Event-based Programming: Motivation

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- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …

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  - …
- Events: *restructure programming model to have no threads!*

Event Programming Model Basics

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    - create_event_queue(handler) → event_q
    - enqueue_event(event_q, event-object)
        - Invokes handler (eventually)

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    - create_event_queue(handler) → event_q
    - enqueue_event(event_q, event-object)
        - Invokes handler (eventually)
- Scheduler decides which event to execute next
    - E.g. based on priority, CPU usage, etc.

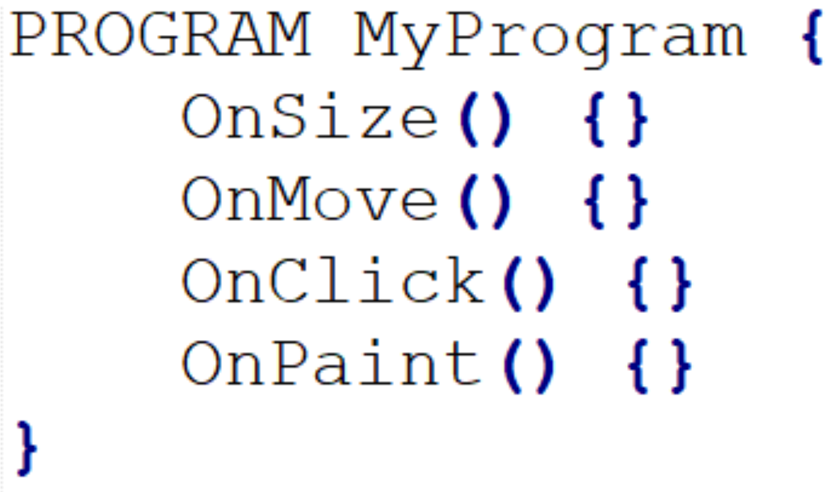
Event-based programming

Event-based programming

```
switch (message)
{
        //case WM_COMMAND:
          // handle menu selections etc.
        //break;
        //case WM_PAINT:
          // draw our window - note: you must paint something here or not trap it!
        //break;
        case WM_DESTROY:
             PostQuitMessage(0);
        break;
        default:
            // We do not want to handle this message so pass back to Windows
            // to handle it in a default way
            return DefWindowProc(hWnd, message, wParam, lParam);
}
```

Event-based programming

Event-based programming



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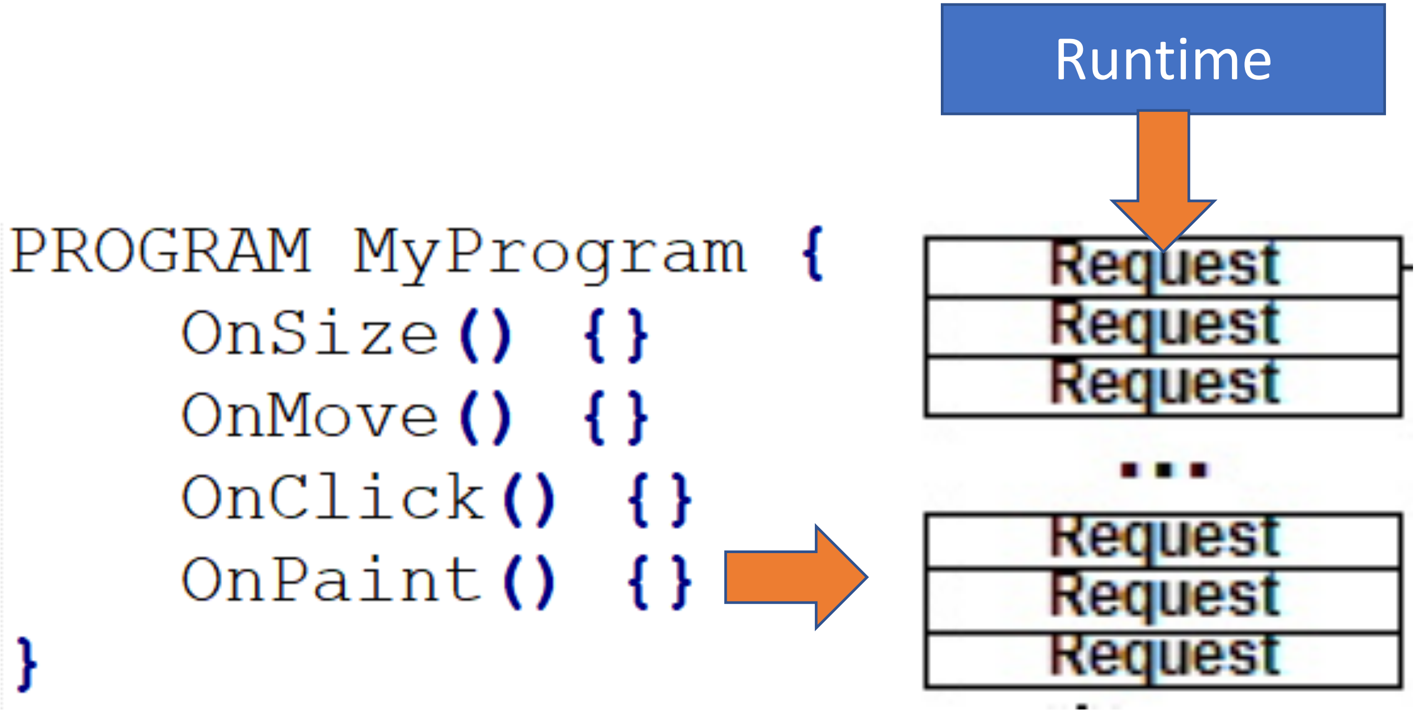
Event-based programming



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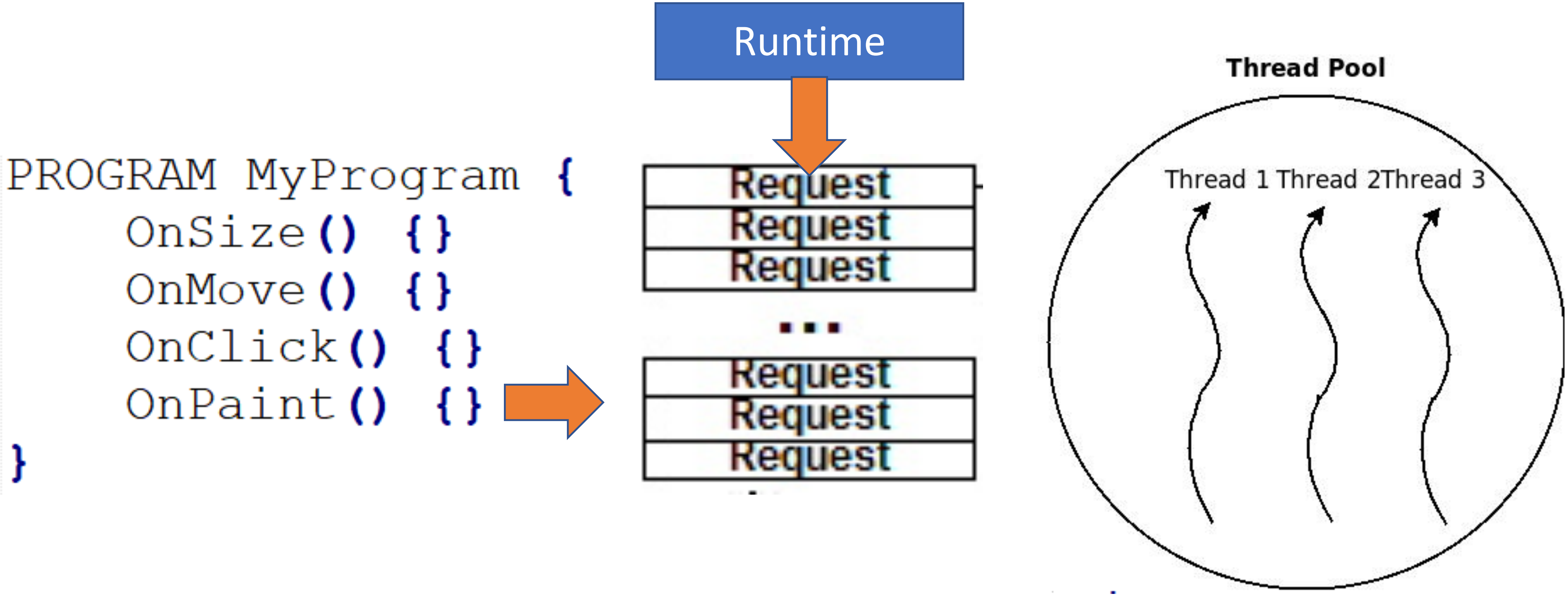

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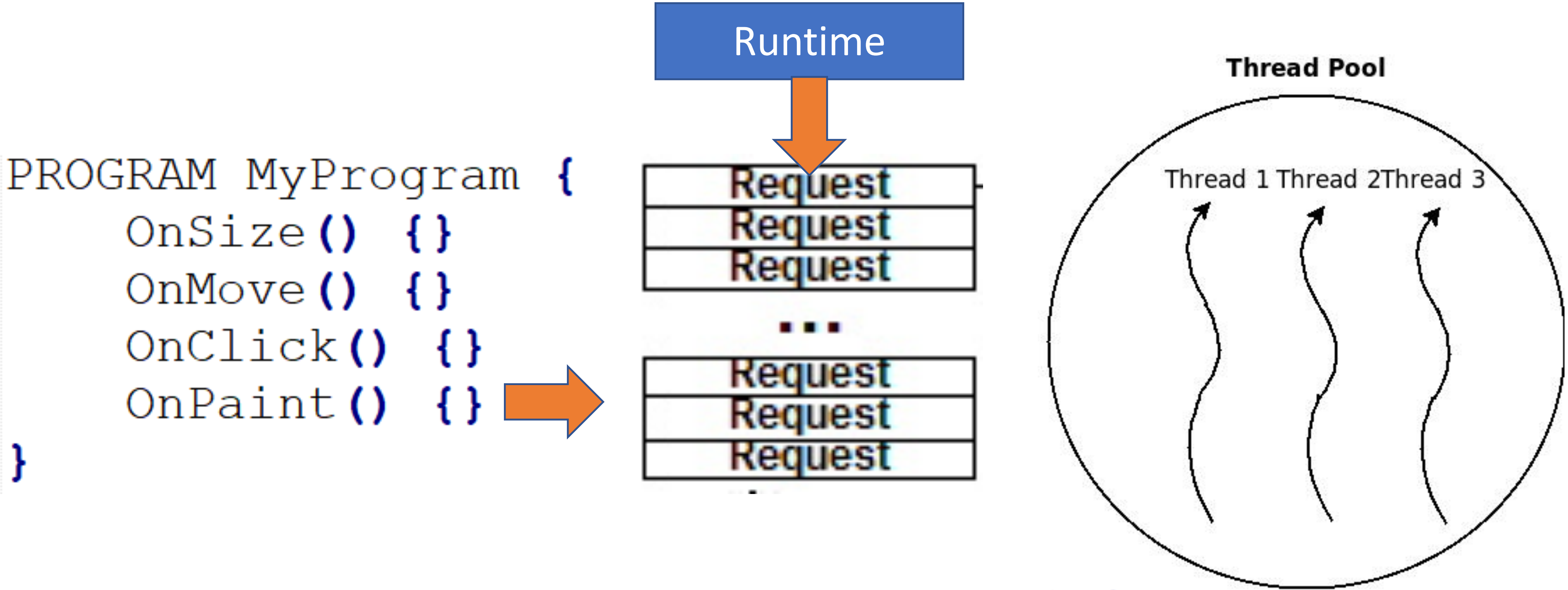

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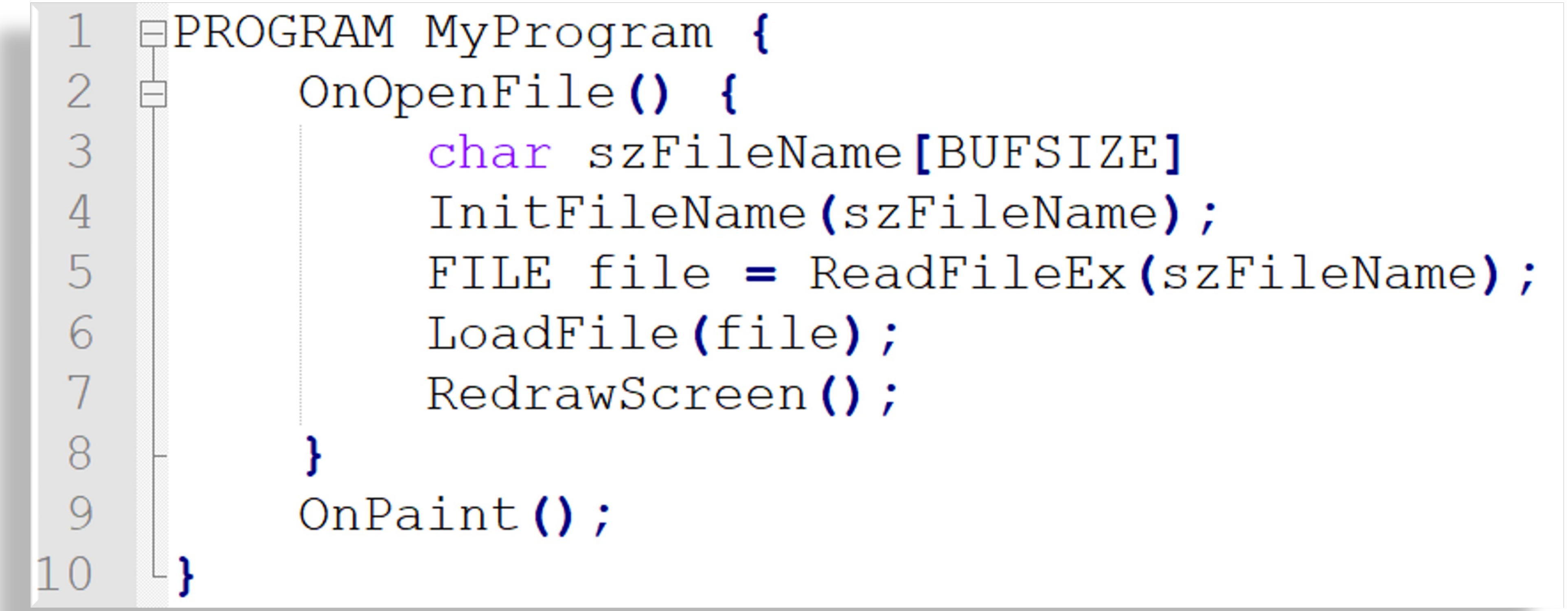
Is the problem solved?

Another Event-based Program

Another Event-based Program



```
PROGRAM MyProgram {
    OnOpenFile() {
        char szFileName[BUFSIZE]
        InitFileName(szFileName);
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        LoadFile(file);
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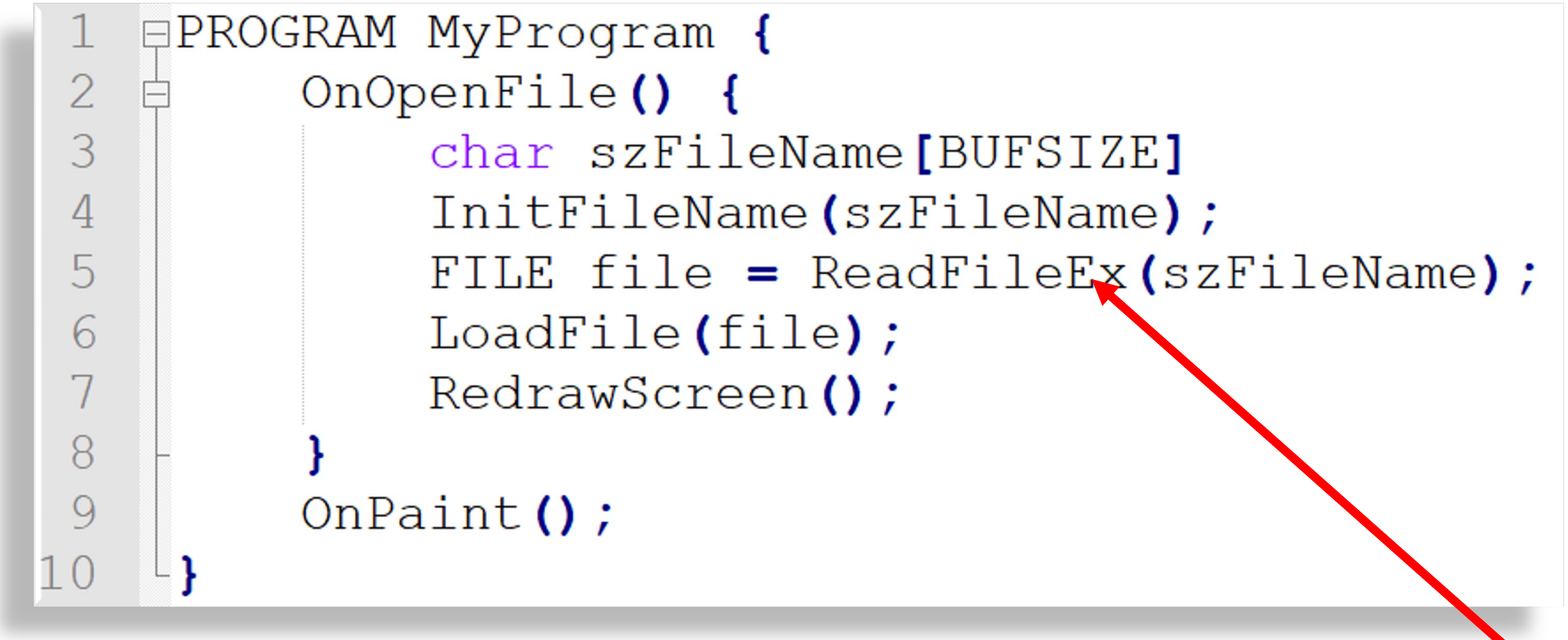
Another Event-based Program



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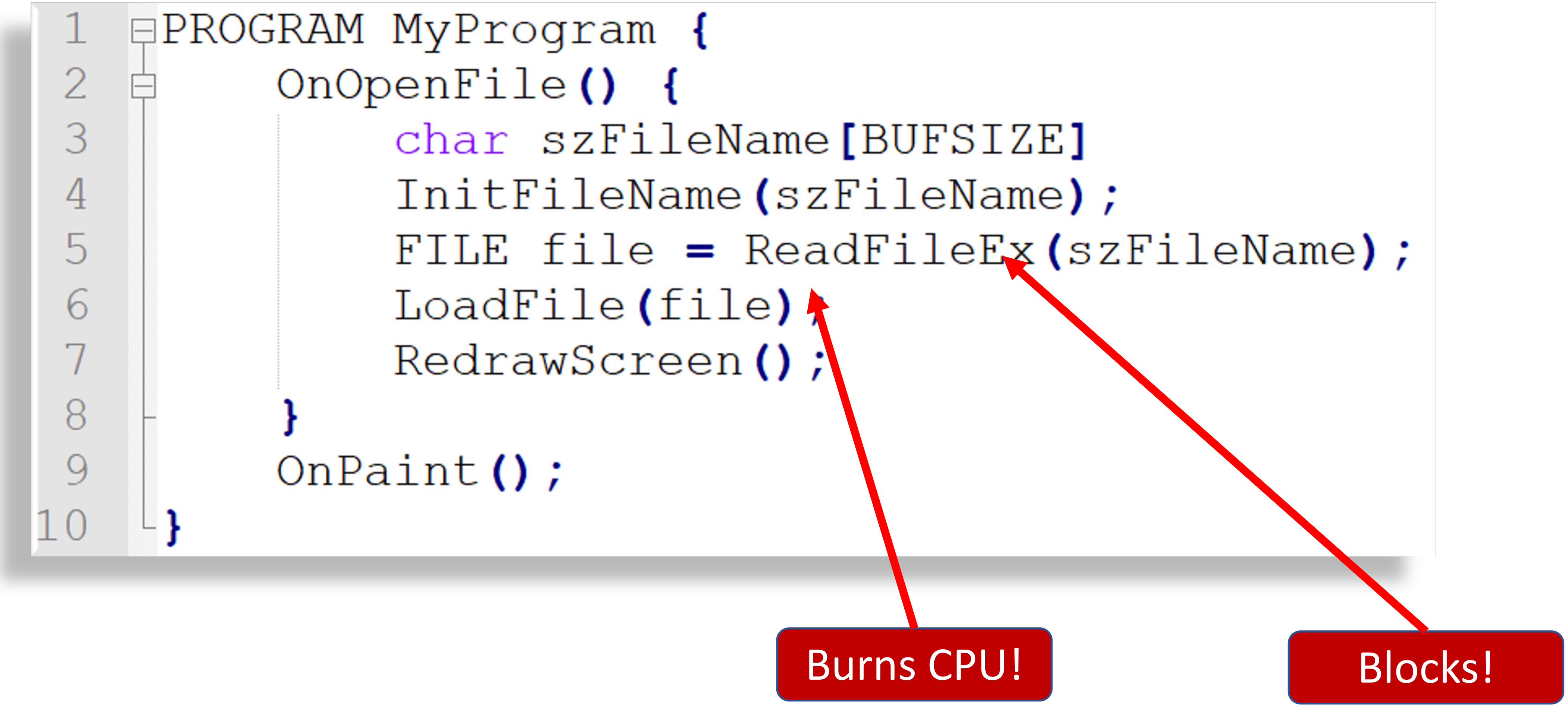
Blocks!

Another Event-based Program



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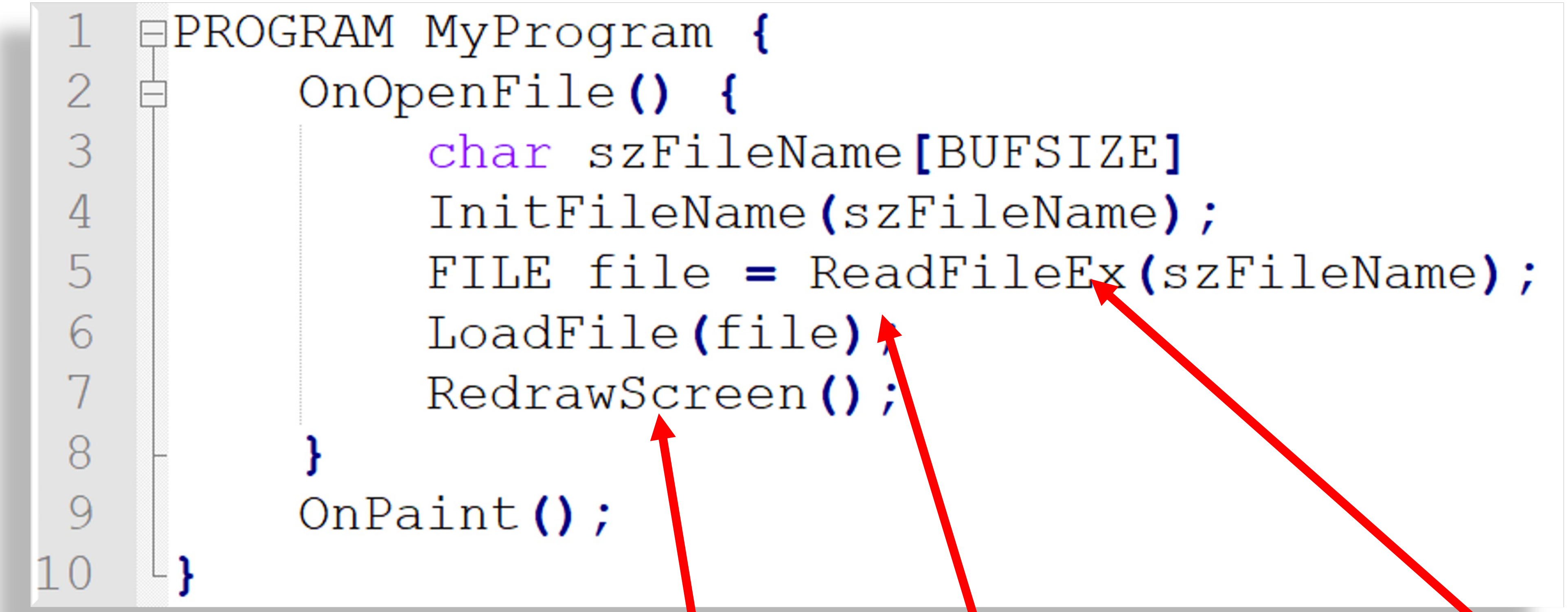
Burns CPU!

Blocks!

Another Event-based Program



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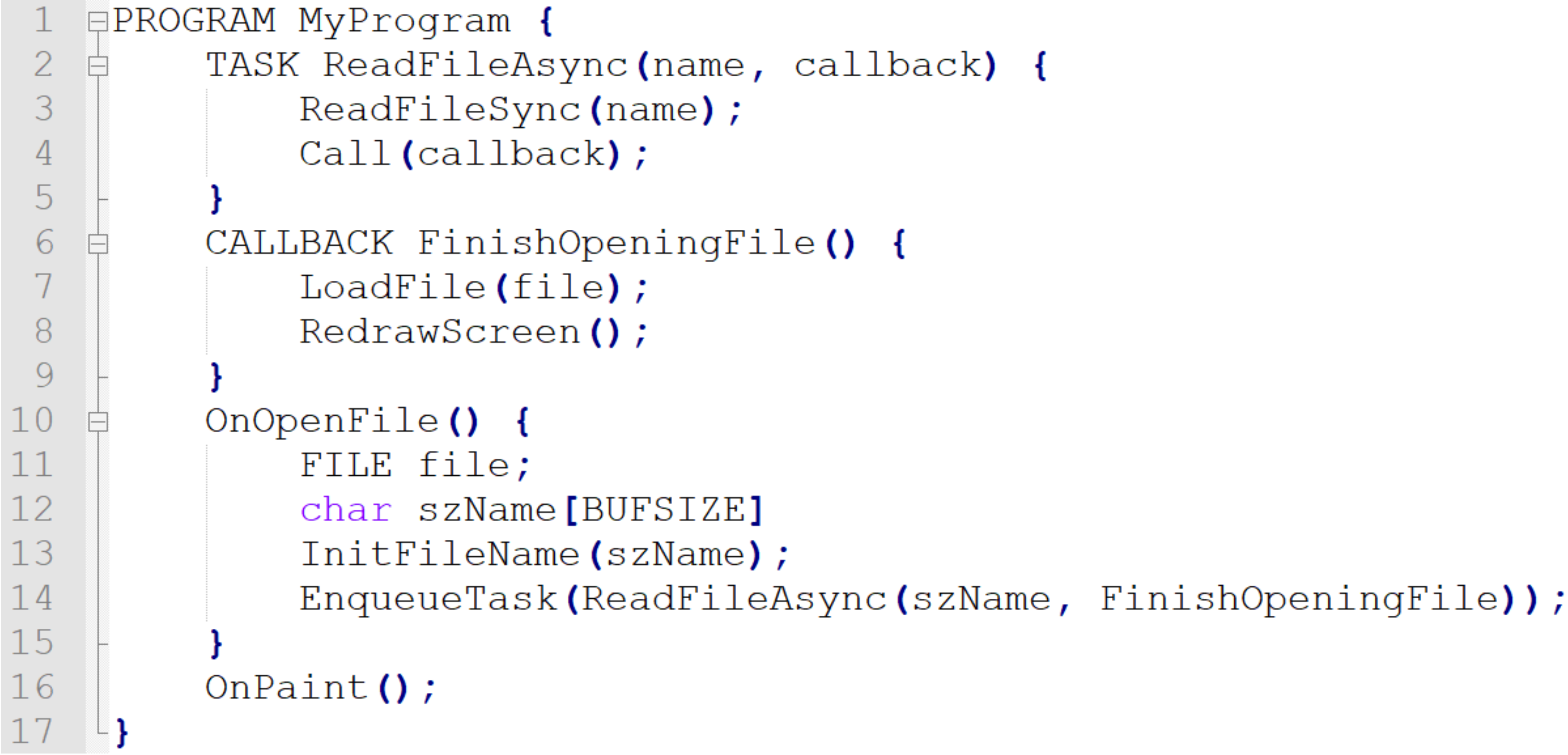
Uses Other Handlers!
(call OnPaint?)

Burns CPU!

Blocks!

No problem! Just use more events/handlers, right?



```
PROGRAM MyProgram {
    TASK ReadFileAsync(name, callback) {
        ReadFileSync(name);
        Call(callback);
    }
    CALLBACK FinishOpeningFile() {
        LoadFile(file);
        RedrawScreen();
    }
    OnOpenFile() {
        FILE file;
        char szName[BUFSIZE]
        InitFileName(szName);
        EnqueueTask(ReadFileAsync(szName, FinishOpeningFile));
    }
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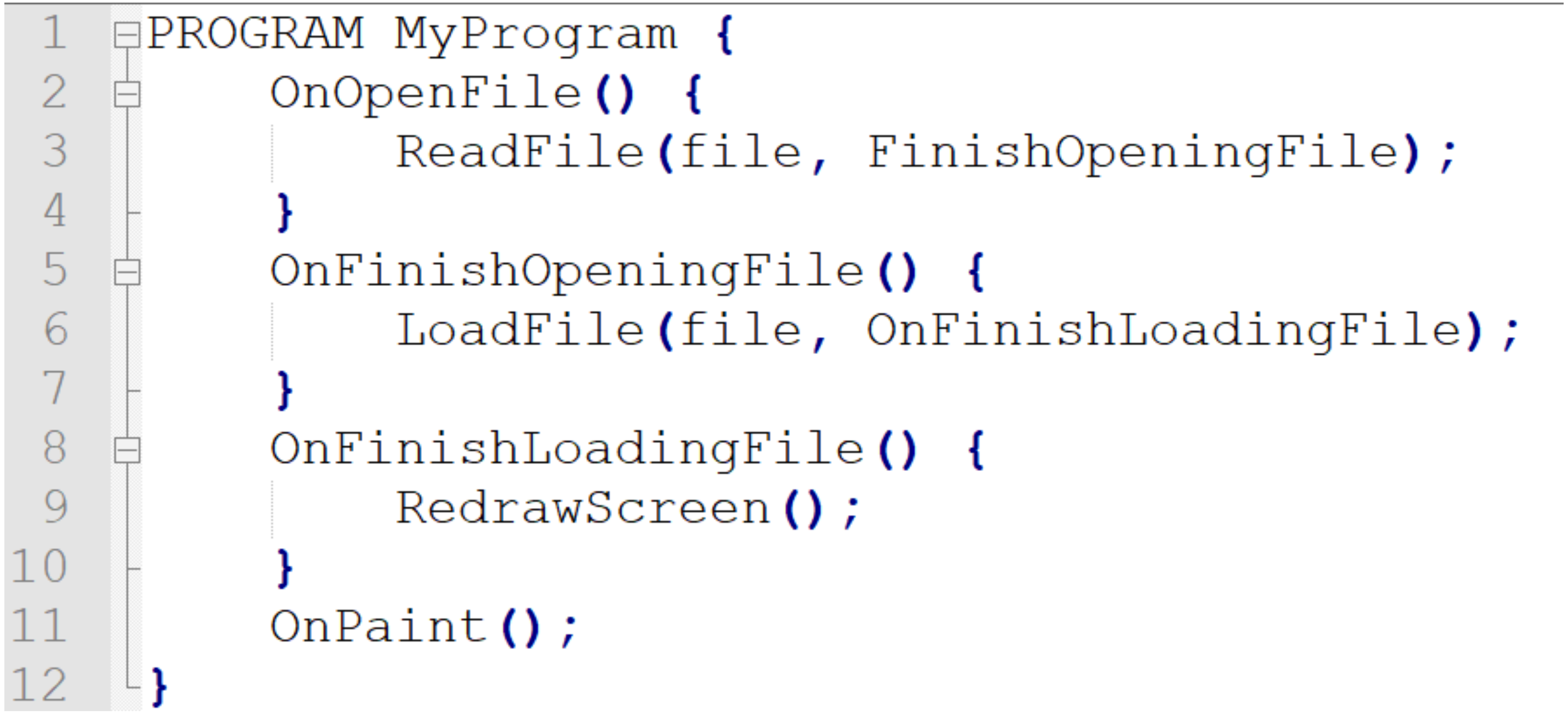
}
```

Continuations, BTW



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PROGRAM MyProgram {
    OnOpenFile() {
        ReadFile(file, FinishOpeningFile);
    }
    OnFinishOpeningFile() {
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    }
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    }
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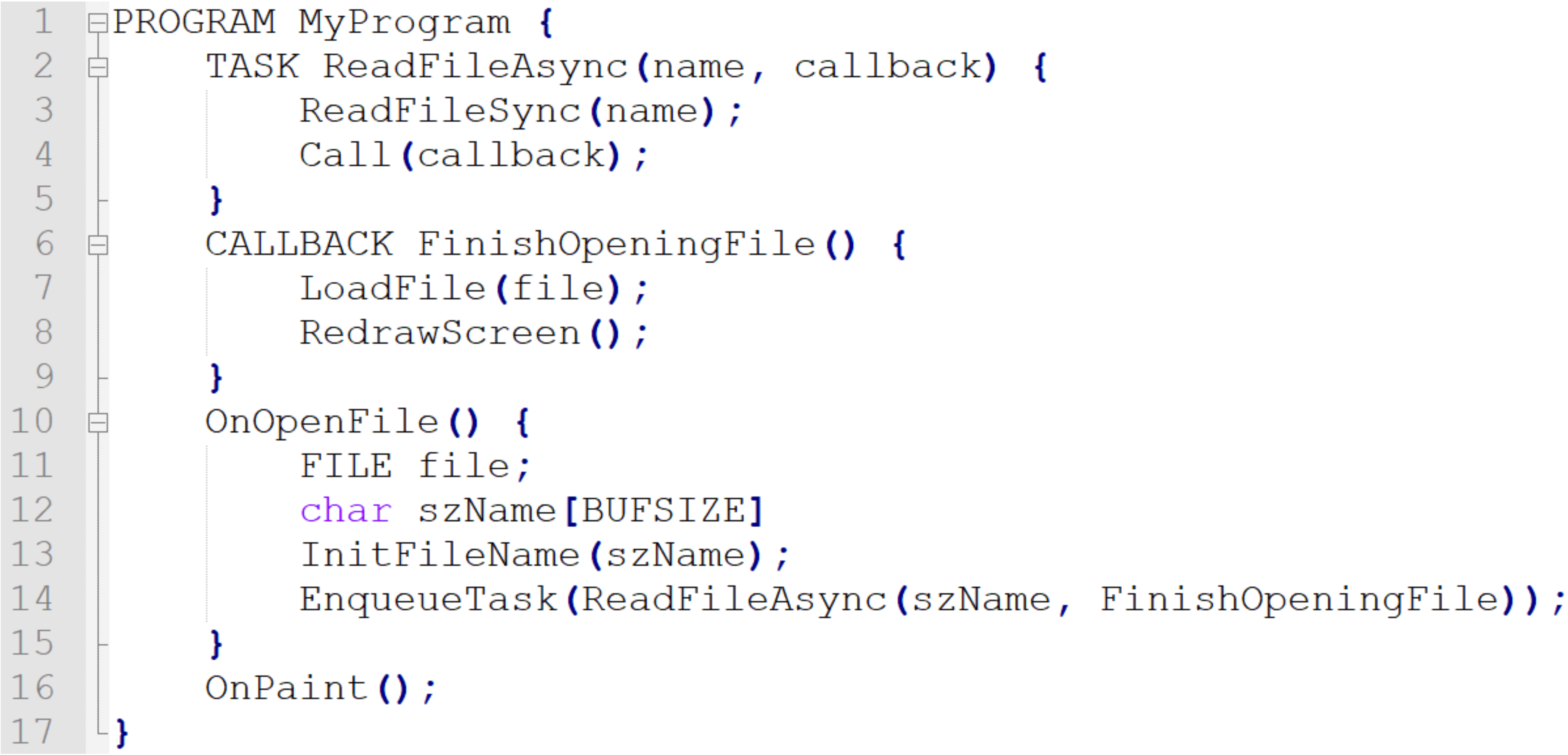
```

Stack-Ripping



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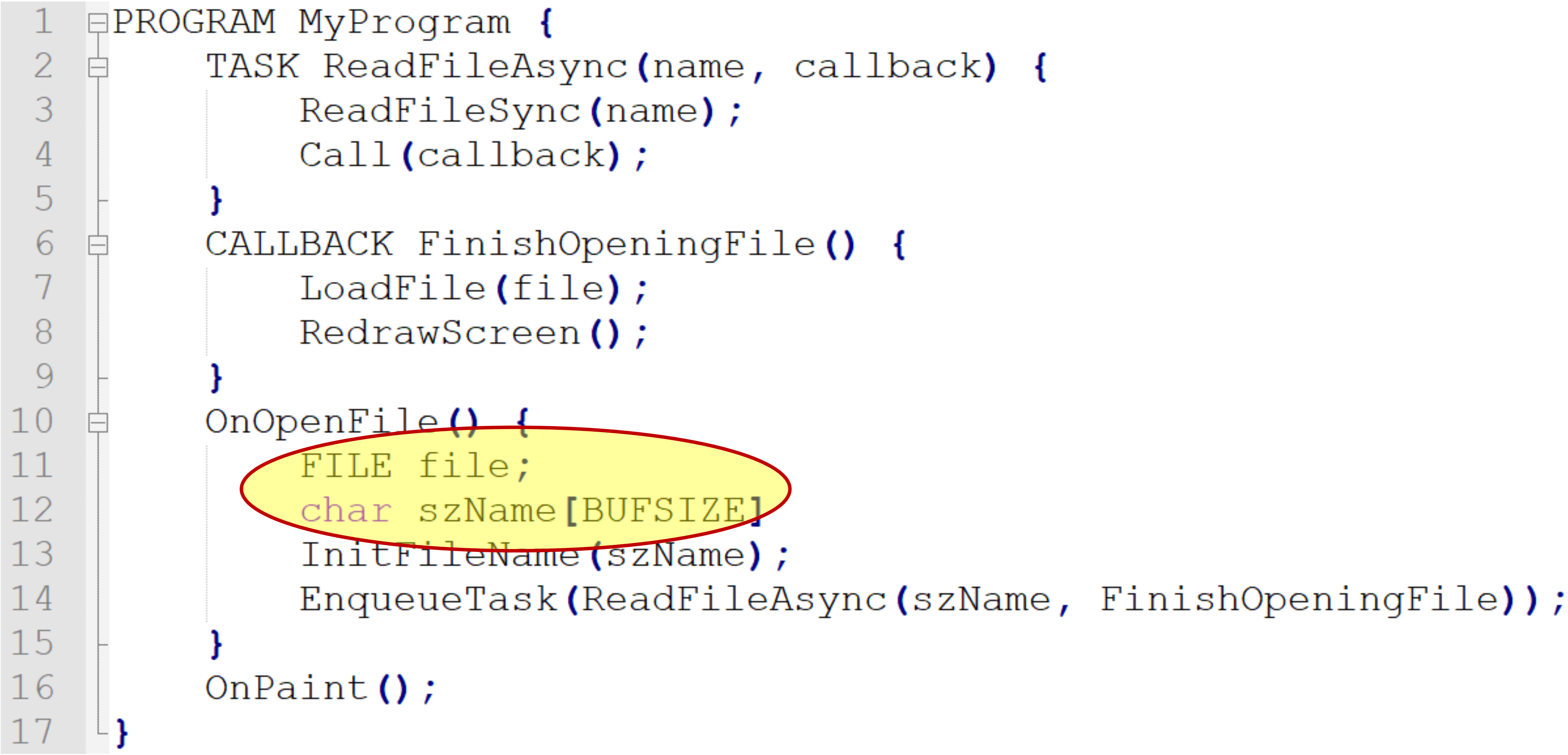

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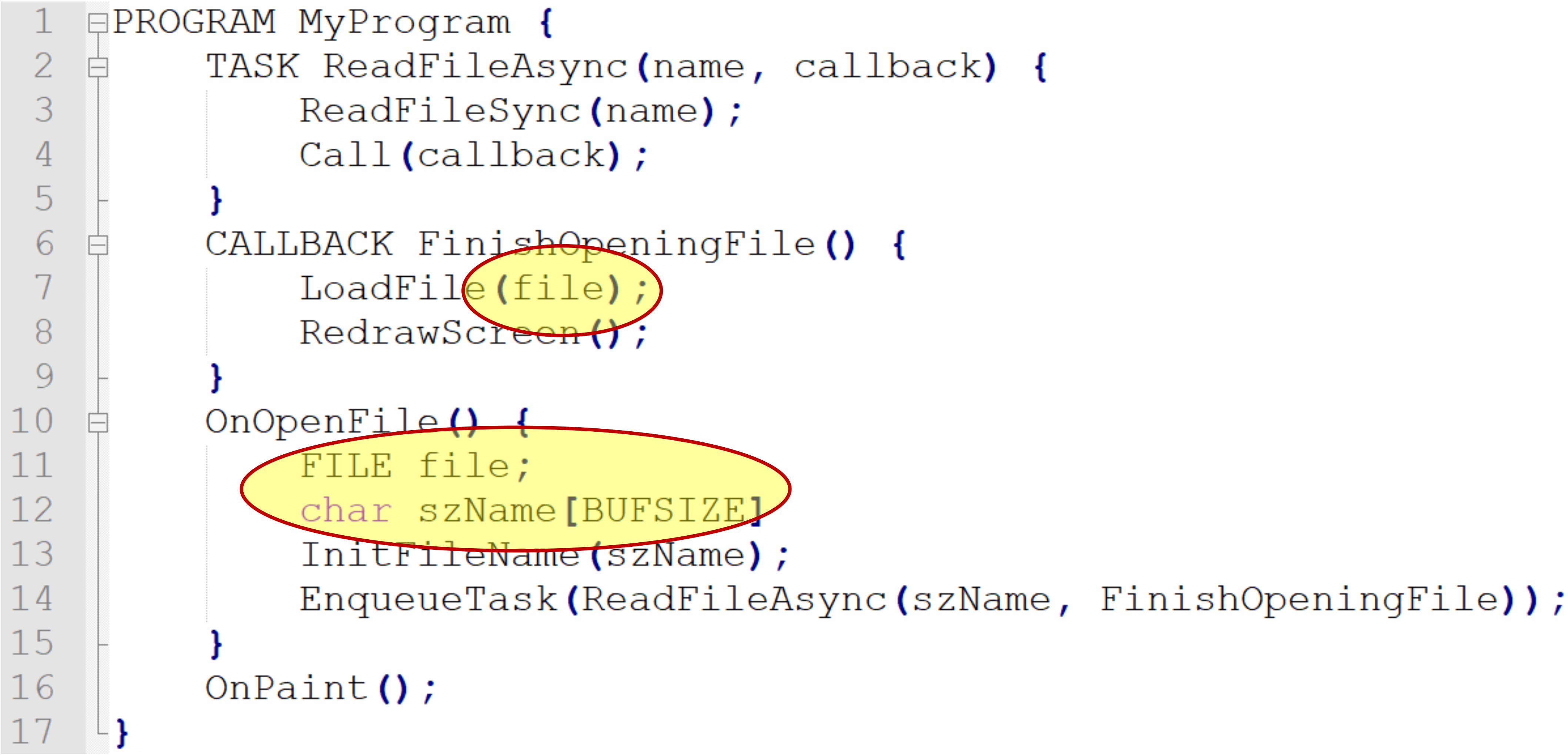

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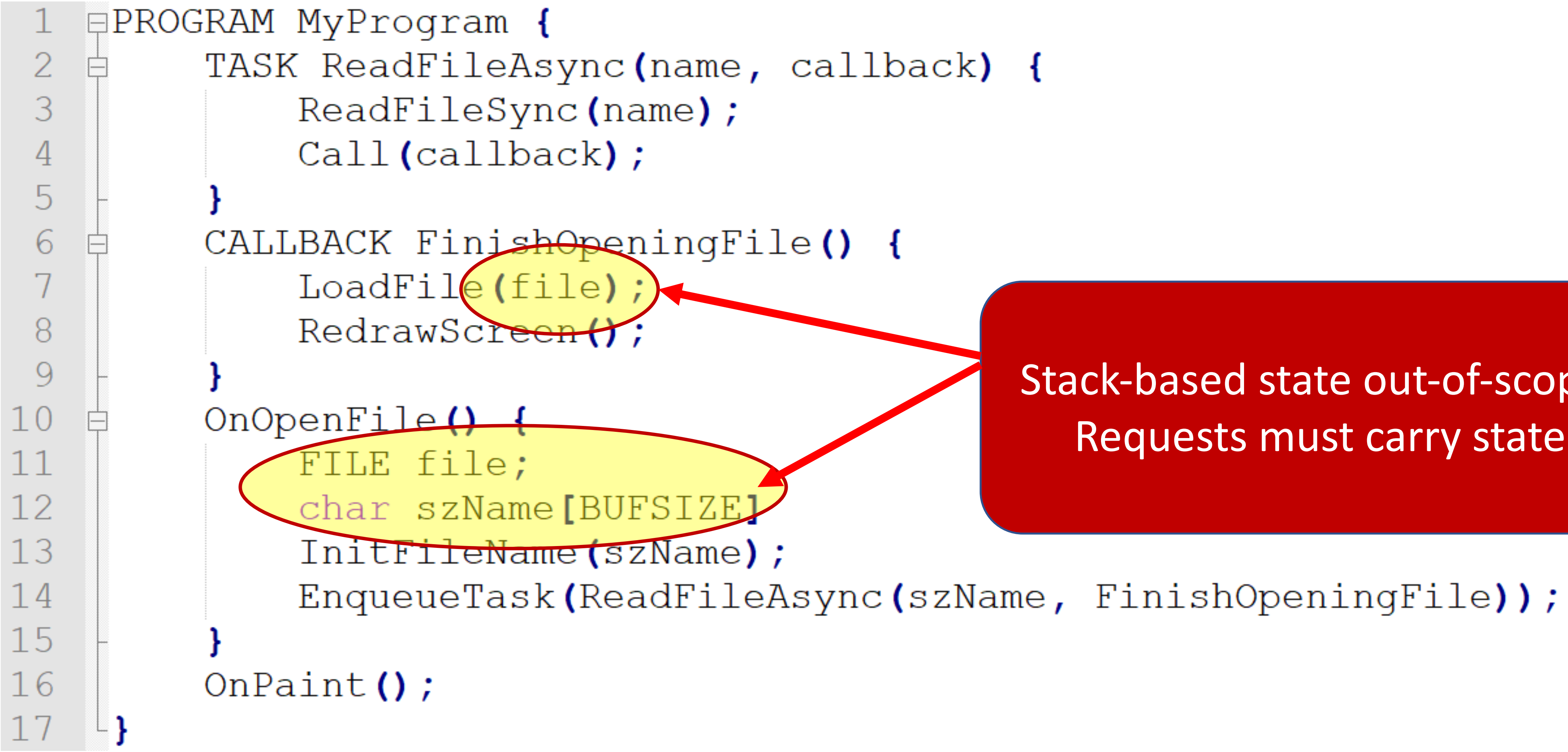

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Stack-based state out-of-scope!

Requests must carry state

Threads vs Events

- Thread Pros
- Thread Cons

- Event Pros
- Event Cons

Threads vs Events

- Thread Pros
  - Overlap I/O and computation
    - While looking sequential
  - Intermediate state on stack
  - Control flow naturally expressed
- Thread Cons
  - Synchronization required
  - Overflowable stack
  - Stack memory pressure

- Event Pros
  - Easier to create well-conditioned system
  - Easier to express dynamic change in level of parallelism
- Event Cons
  - Difficult to program
  - Control flow between callbacks obscure
  - When to deallocate memory
  - Incomplete language/tool/debugger support
  - Difficult to exploit concurrent hardware

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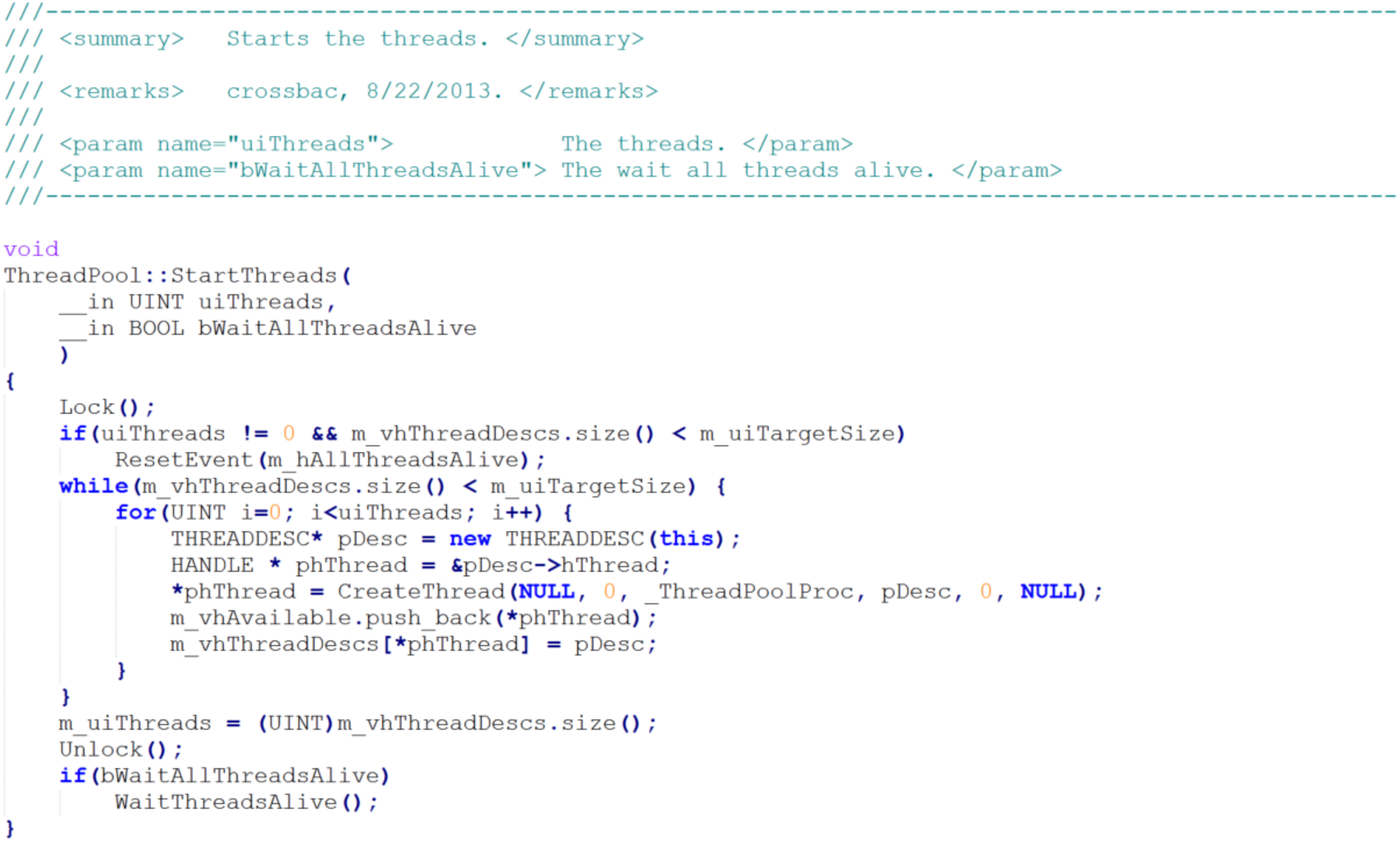
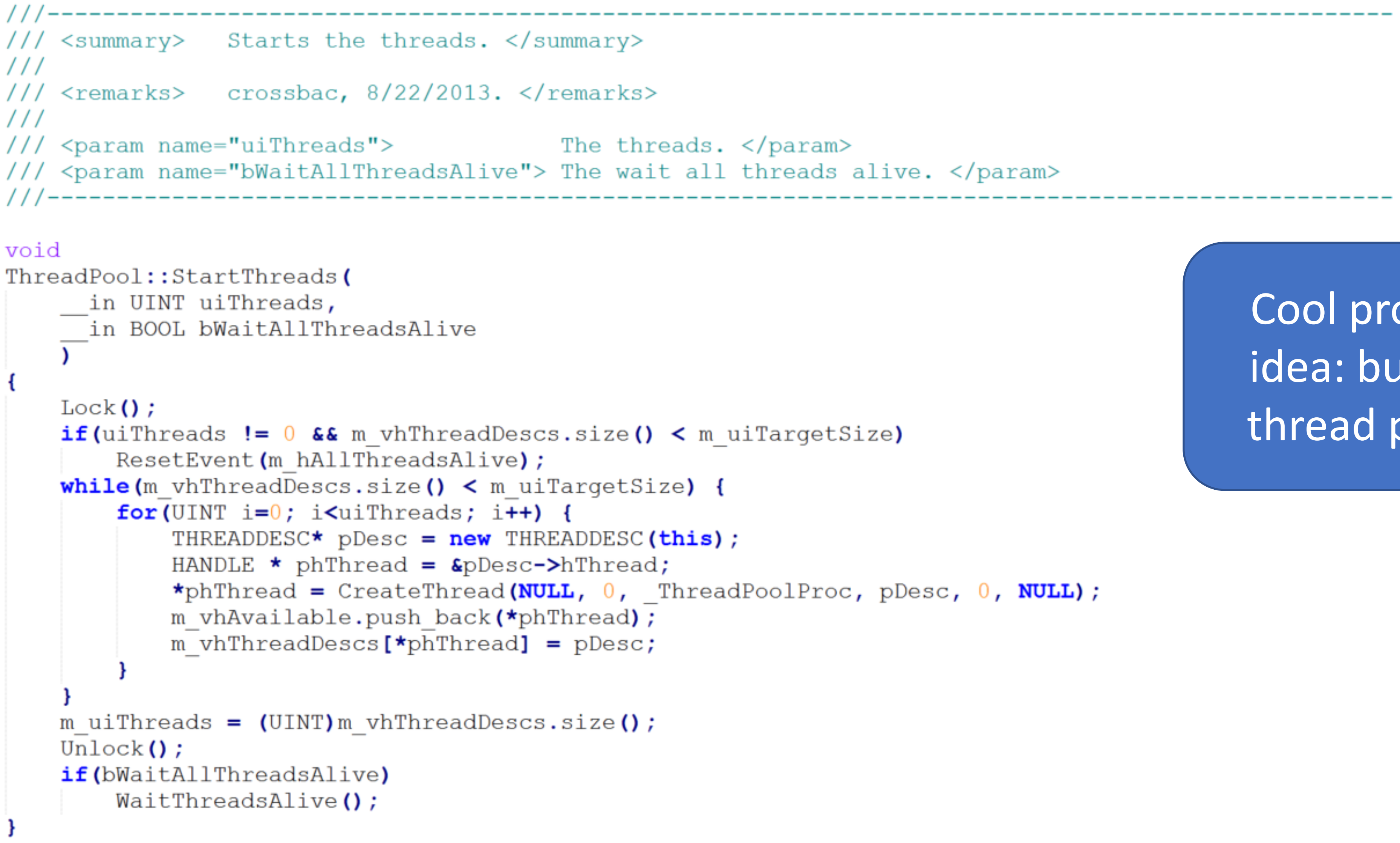
Thread Pool Implementation



```
///-------------------------------------------------------------------------------------------------
/// <summary>   Starts the threads. </summary>
///
/// <remarks>   crossbac, 8/22/2013. </remarks>
///
/// <param name="uiThreads">            The threads. </param>
/// <param name="bWaitAllThreadsAlive"> The wait all threads alive. </param>
///-------------------------------------------------------------------------------------------------

void
ThreadPool::StartThreads(
    __in UINT uiThreads,
    __in BOOL bWaitAllThreadsAlive
    )
{
    Lock();
    if(uiThreads != 0 && m_vhThreadDescs.size() < m_uiTargetSize)
        ResetEvent(m_hAllThreadsAlive);
    while(m_vhThreadDescs.size() < m_uiTargetSize) {
        for(UINT i=0; i<uiThreads; i++) {
            THREADDESC* pDesc = new THREADDESC(this);
            HANDLE * phThread = &pDesc->hThread;
            *phThread = CreateThread(NULL, 0, _ThreadPoolProc, pDesc, 0, NULL);
            m_vhAvailable.push_back(*phThread);
            m_vhThreadDescs[*phThread] = pDesc;
        }
    }
    m_uiThreads = (UINT)m_vhThreadDescs.size();
    Unlock();
    if(bWaitAllThreadsAlive)
        WaitThreadsAlive();
}
```

Thread Pool Implementation



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        ResetEvent(m_hAllThreadsAlive);
    while(m_vhThreadDescs.size() < m_uiTargetSize) {
        for(UINT i=0; i<uiThreads; i++) {
            THREADDESC* pDesc = new THREADDESC(this);
            HANDLE * phThread = &pDesc->hThread;
            *phThread = CreateThread(NULL, 0, _ThreadPoolProc, pDesc, 0, NULL);
            m_vhAvailable.push_back(*phThread);
            m_vhThreadDescs[*phThread] = pDesc;
        }
    }
    m_uiThreads = (UINT)m_vhThreadDescs.size();
    Unlock();
    if(bWaitAllThreadsAlive)
        WaitThreadsAlive();
}
```

Cool project idea: build a thread pool!

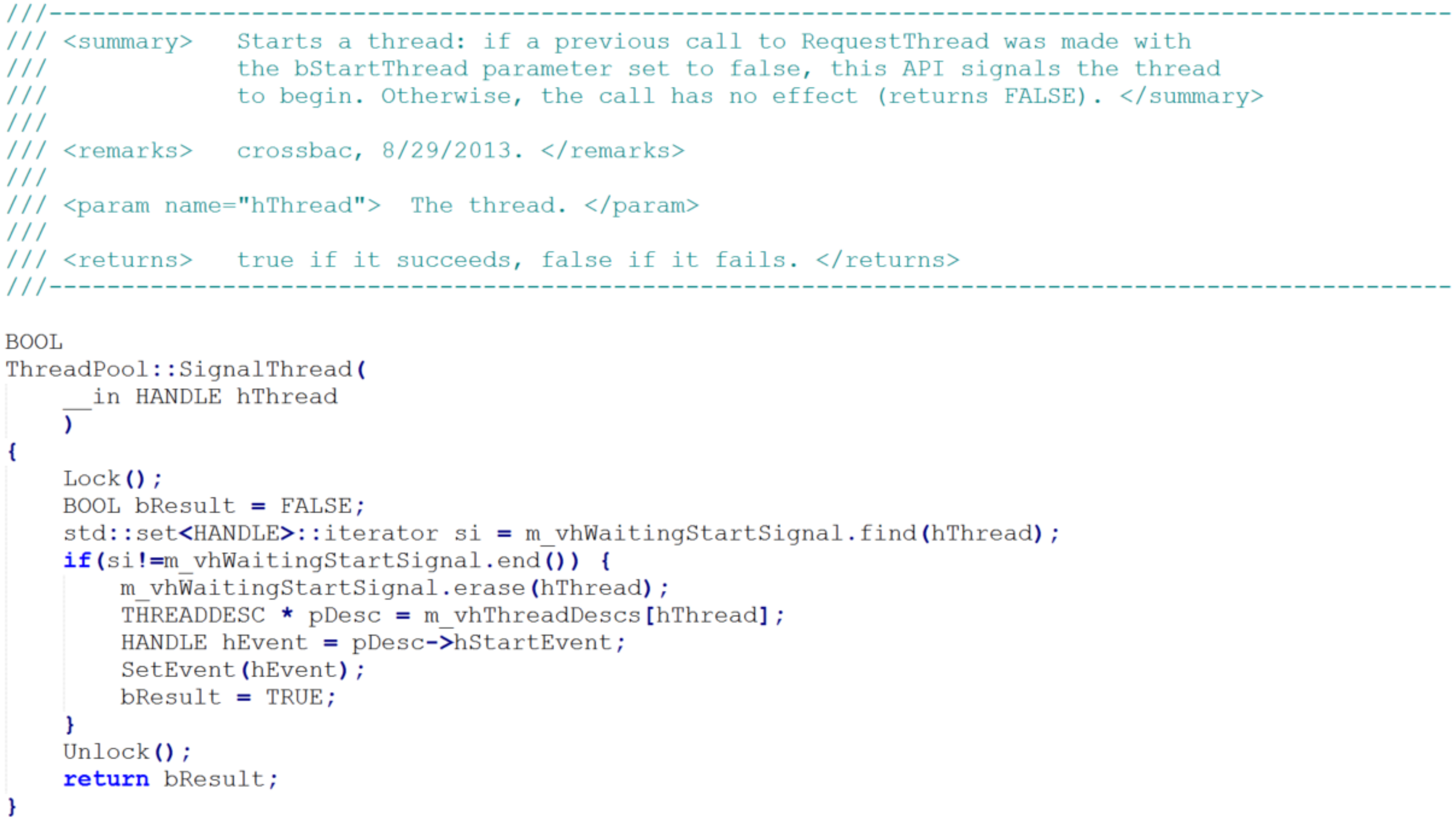
Thread Pool Implementation

```
DWORD
ThreadPool::ThreadPoolProc(
    __in THREADDESC * pDesc
    )
{
    HANDLE hThread = pDesc->hThread;
    HANDLE hStartEvent = pDesc->hStartEvent;
    HANDLE hRuntimeTerminate = PTask::Runtime::GetRuntimeTerminateEvent();
    HANDLE vEvents[] = { hStartEvent, hRuntimeTerminate };


    NotifyThreadAlive(hThread);
    while(!pDesc->bTerminate) {

        DWORD dwWait = WaitForMultipleObjects(dwEvents, vEvents, FALSE, INFINITE);
        pDesc->Lock();
        pDesc->bTerminate |= bTerminate;
        if(pDesc->bRoutineValid && !pDesc->bTerminate) {
            LPTHREAD_START_ROUTINE lpRoutine = pDesc->lpRoutine;
            LPVOID lpParameter = pDesc->lpParameter;
            pDesc->bActive = TRUE;
            pDesc->Unlock();
            dwResult = (*lpRoutine)(lpParameter);
            pDesc->Lock();
            pDesc->bActive = FALSE;
            pDesc->bRoutineValid = FALSE;
        }
        pDesc->Unlock();
        Lock();
        m_vhInFlight.erase(pDesc->hThread);
        if(!pDesc->bTerminate)
            m_vhAvailable.push_back(pDesc->hThread);
        Unlock();
    }
    NotifyThreadExit(hThread);
    return dwResult;
}
```

ThreadPool Implementation



```
///-------------------------------------------------------------------------------------------------
/// <summary>   Starts a thread: if a previous call to RequestThread was made with
///             the bStartThread parameter set to false, this API signals the thread
///             to begin. Otherwise, the call has no effect (returns FALSE). </summary>
///
/// <remarks>   crossbac, 8/29/2013. </remarks>
///
/// <param name="hThread">  The thread. </param>
///
/// <returns>   true if it succeeds, false if it fails. </returns>
///-------------------------------------------------------------------------------------------------

BOOL
ThreadPool::SignalThread(
    __in HANDLE hThread
    )
{
    Lock();
    BOOL bResult = FALSE;
    std::set<HANDLE>::iterator si = m_vhWaitingStartSignal.find(hThread);
    if(si!=m_vhWaitingStartSignal.end()) {
        m_vhWaitingStartSignal.erase(hThread);
        THREADDESC * pDesc = m_vhThreadDescs[hThread];
        HANDLE hEvent = pDesc->hStartEvent;
        SetEvent(hEvent);
        bResult = TRUE;
    }
    Unlock();
    return bResult;
}
```

Redux: Futures in Context

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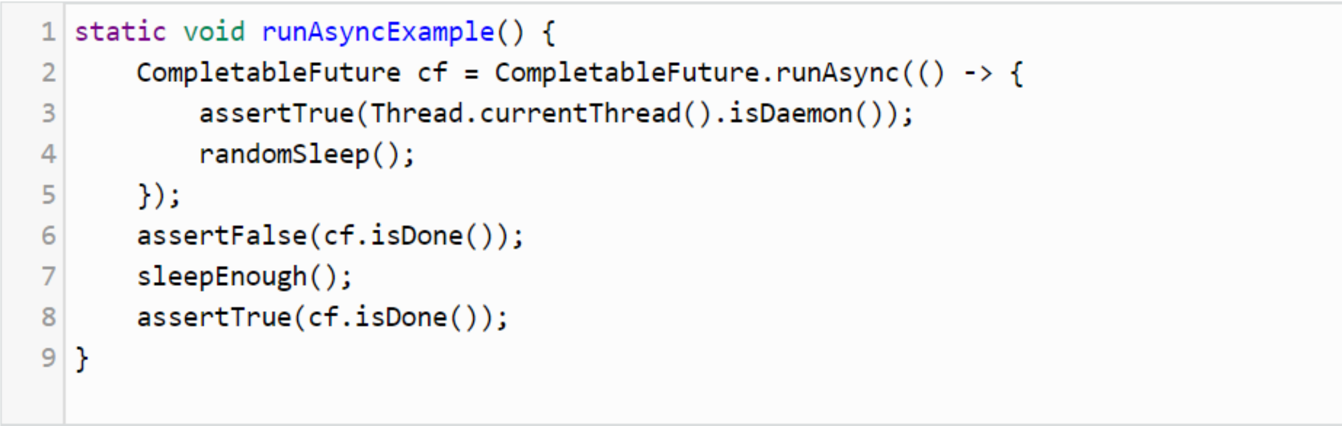

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static void runAsyncExample() {
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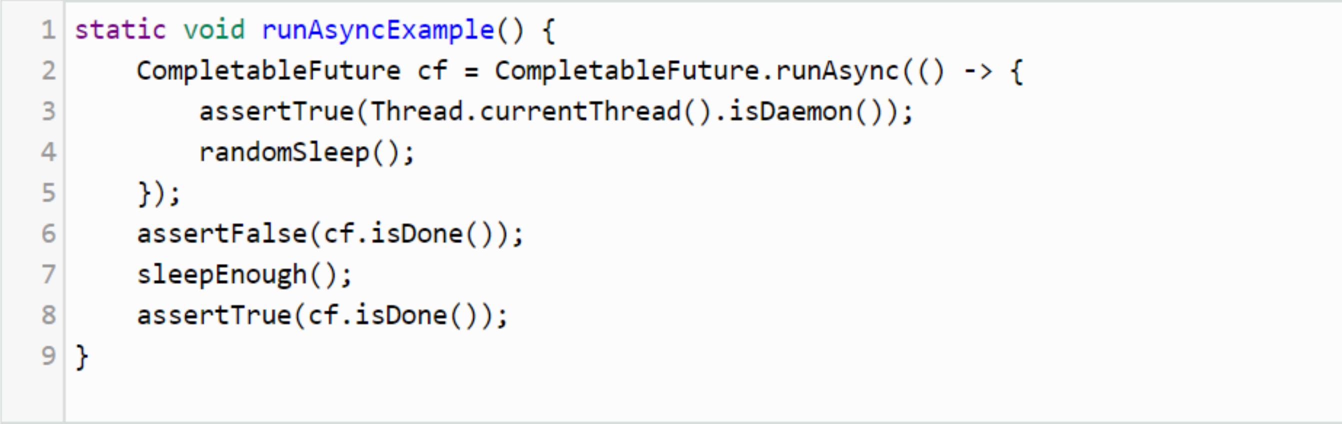

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Compromise Model:

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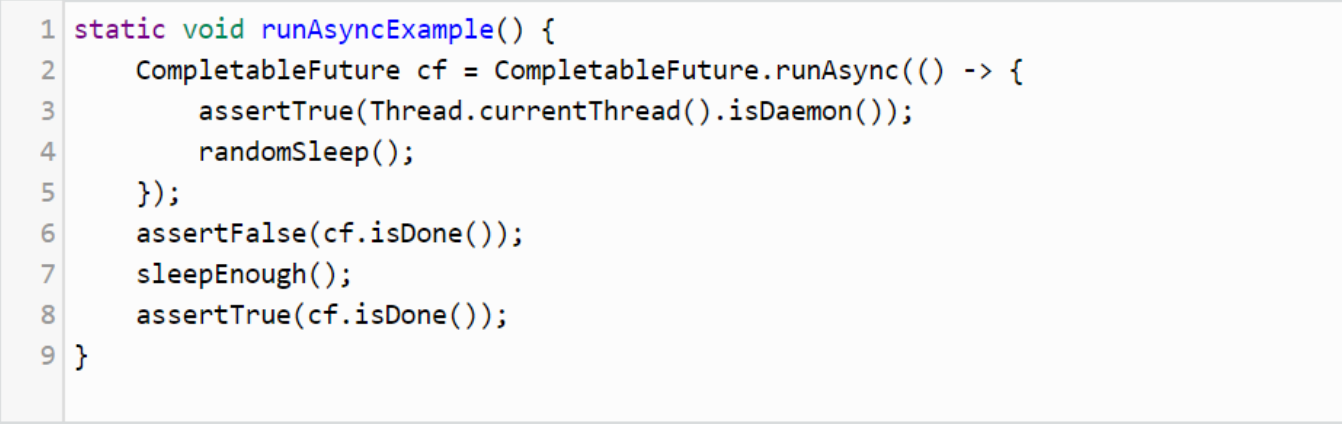

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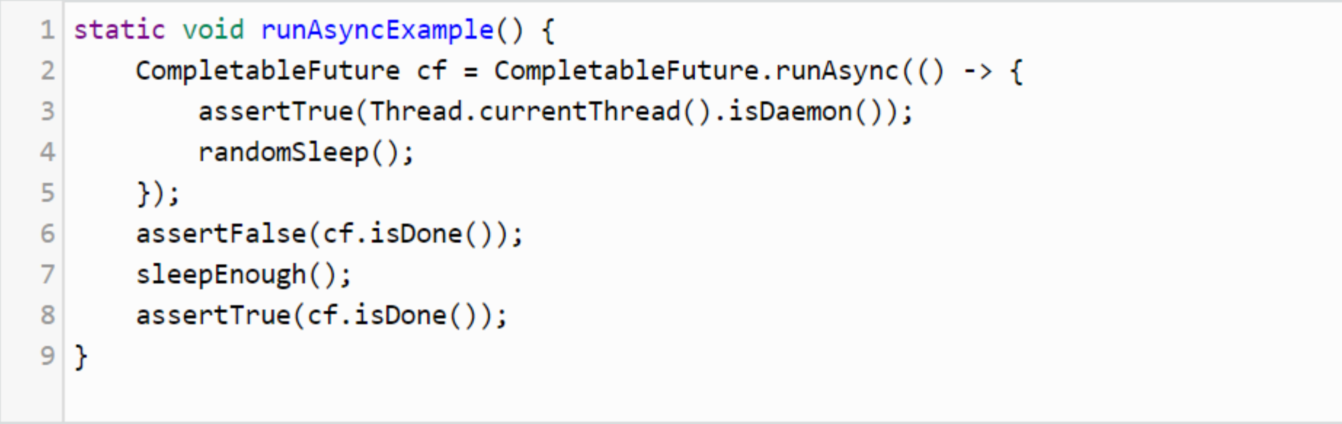

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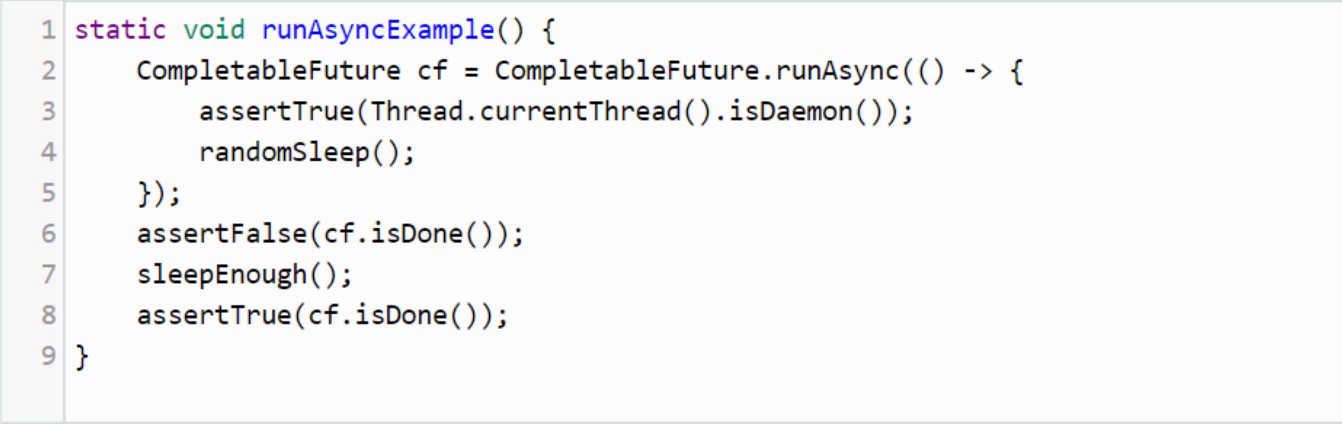
Currently: 2nd renaissance IMHO



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Questions?