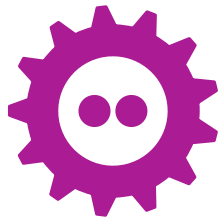
Fair Threaded Task Scheduler Verified in TLA+

Vladislav Shpilevoy

github.com / ubisoft / task-scheduler



FOSDEM'23

UBISOFT

Plan

Task scheduling

Typical solutions

New task scheduler

Scheduling gears

Verification

Benchmarks

Future plans

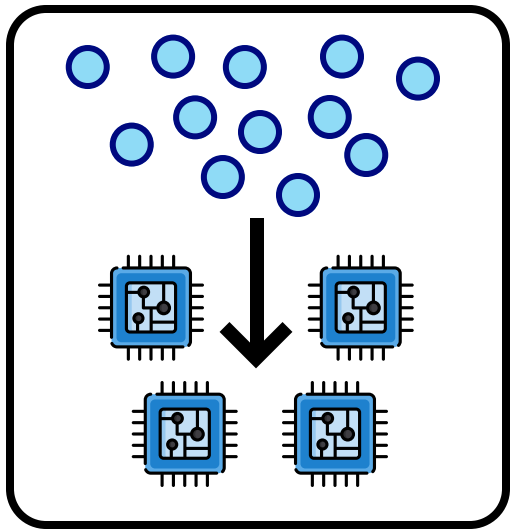
Task scheduling

is just execution of code

Task scheduling

is just execution of code

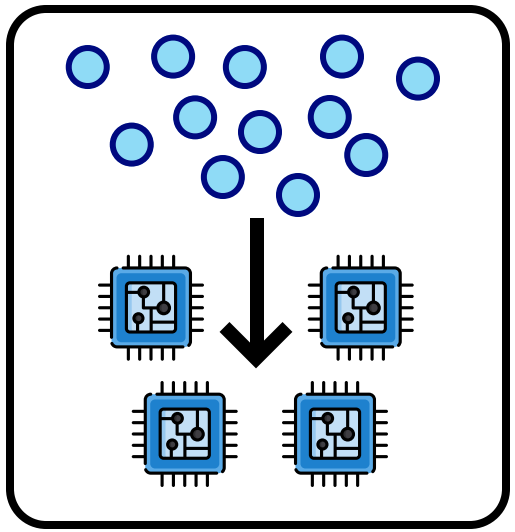
Thread pool



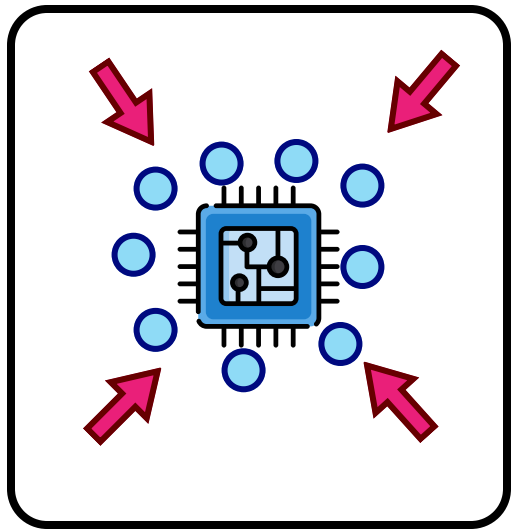
Task scheduling

is just execution of code

Thread pool



Event loop



Task scheduling

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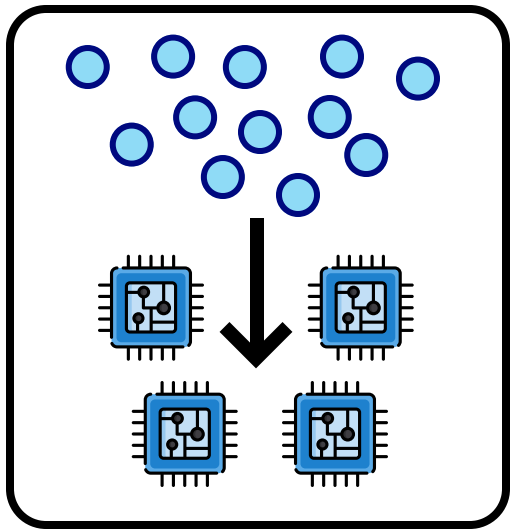

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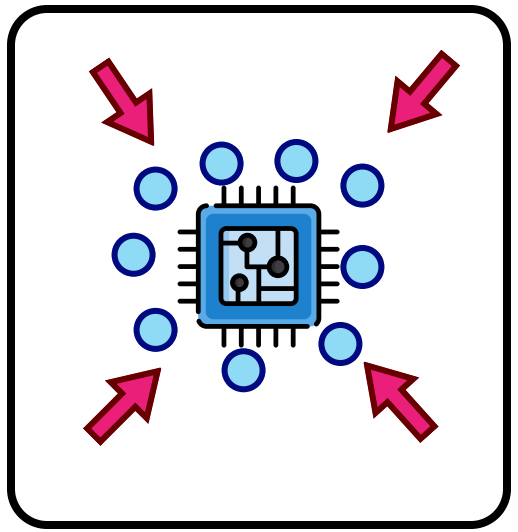
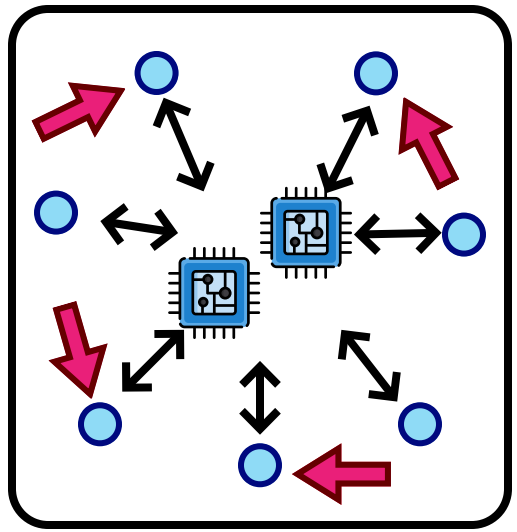


Coroutine engine



Trivial scheduler

```
class TrivialSched:
    Thread              myThread;
    Mutex               myLock;
    ConditionVariable   myCond;
    List<Callback>      myQueue;
```

```
TrivialSched::Post(const Callback& aFunc)
{
    myLock.Lock();
    myQueue.Append(aFunc);
    myCond.Signal();
    myLock.Unlock();
}

TrivialSched::Run()
{
    while(!IsStopped()) {
        myLock.Lock();
        while (myQueue.IsEmpty())
            myCond.Wait();
        Callback cb = myQueue.Pop();
        myLock.Unlock();

        cb.Execute();
    }
}
```

Trivial scheduler

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Single thread

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Single thread

Simple locked queue

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Append under a lock

Pop under a lock

Trivial scheduler

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Single thread

Simple locked queue

Grind the tasks one by one

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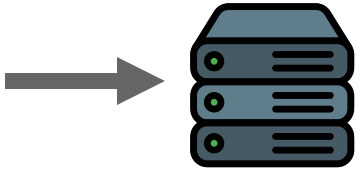
Execute one by one

The real task

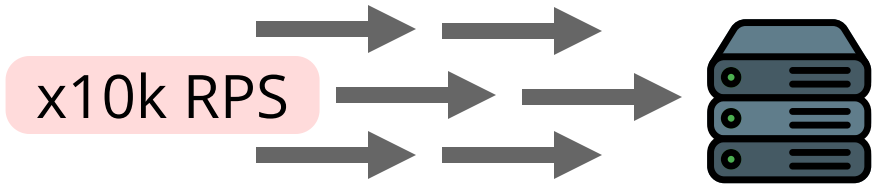
The real task

Handling savegames



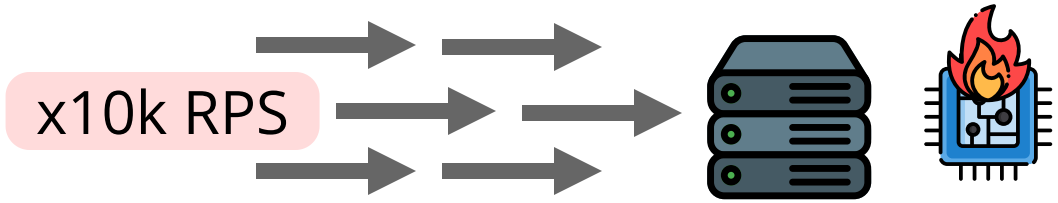
The real task

Handling savegames



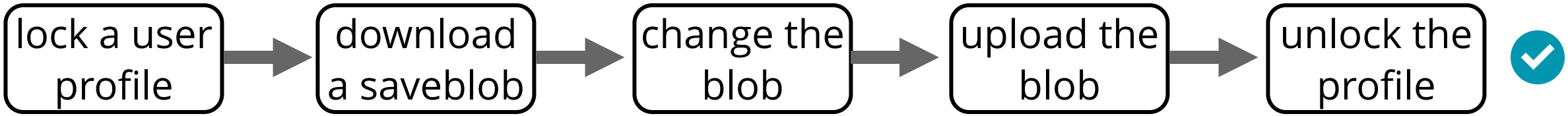
The real task

Handling savegames



CPU-intensive

Multiple steps:



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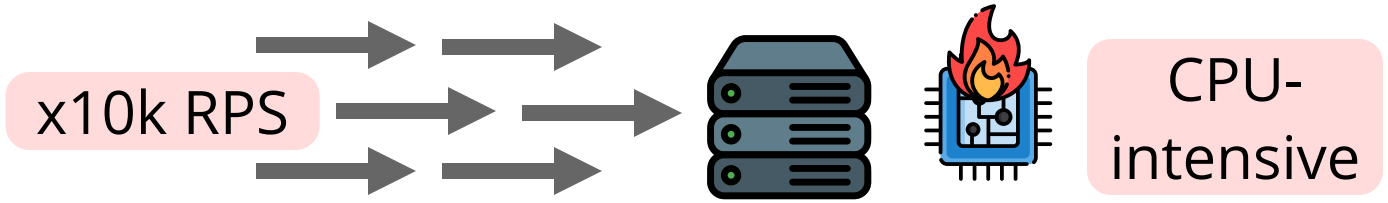
Handling savegames



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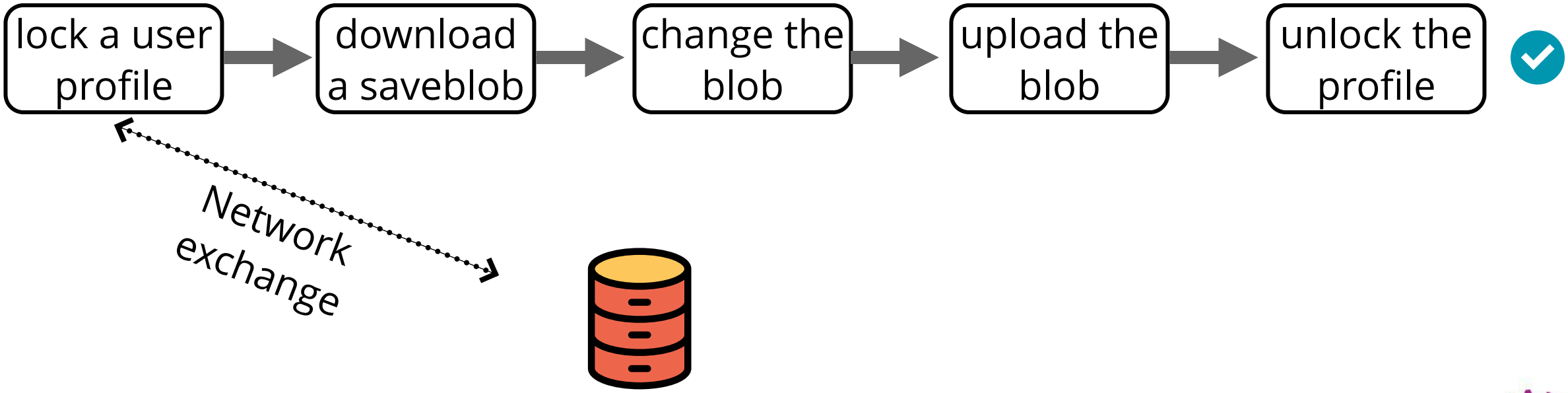
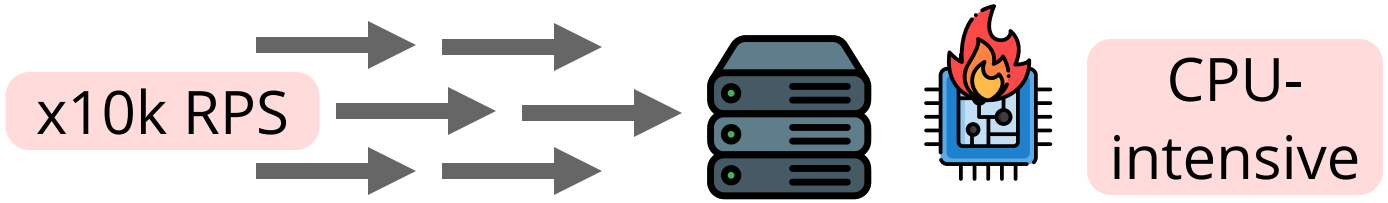


The real task

Handling savegames



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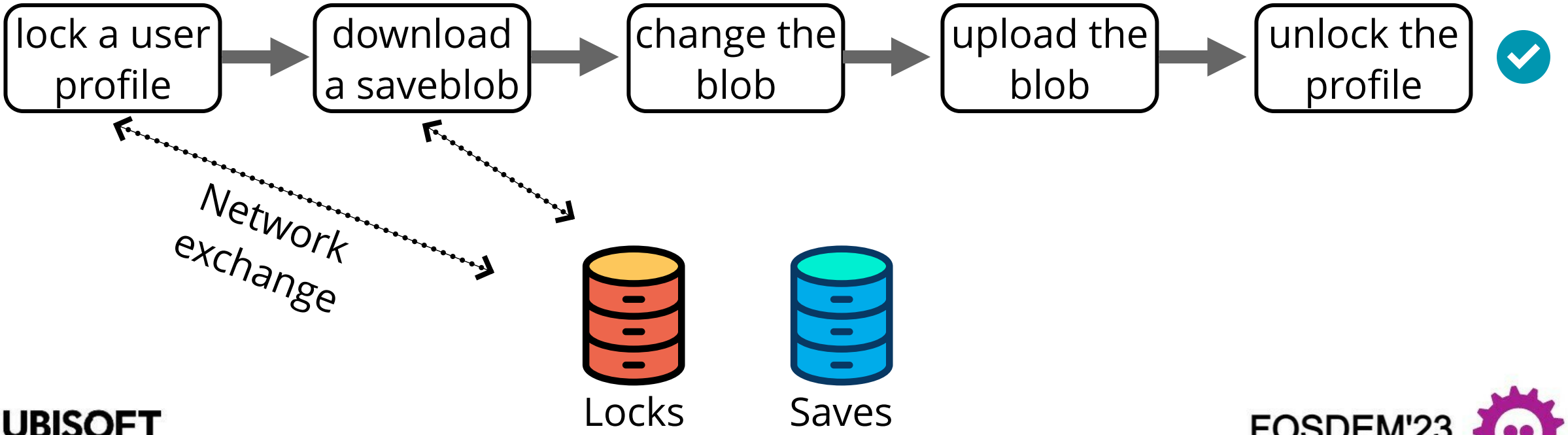

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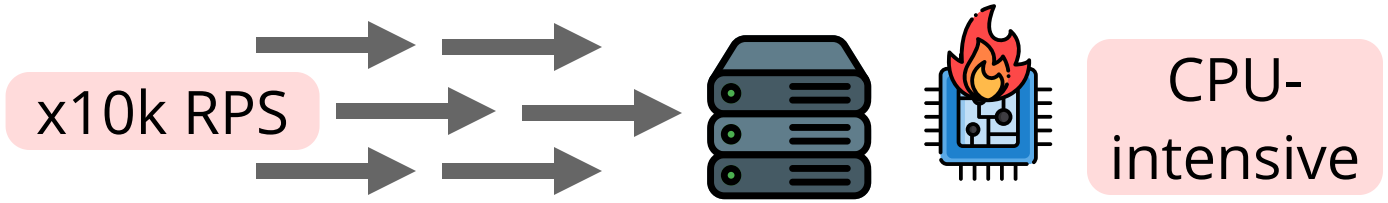
Handling savegames



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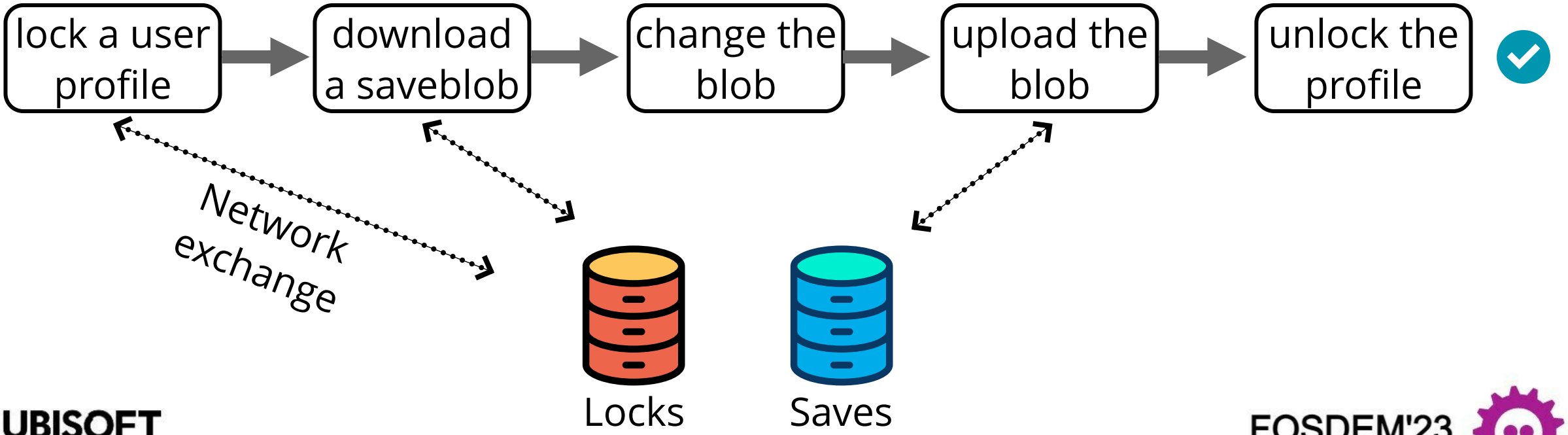

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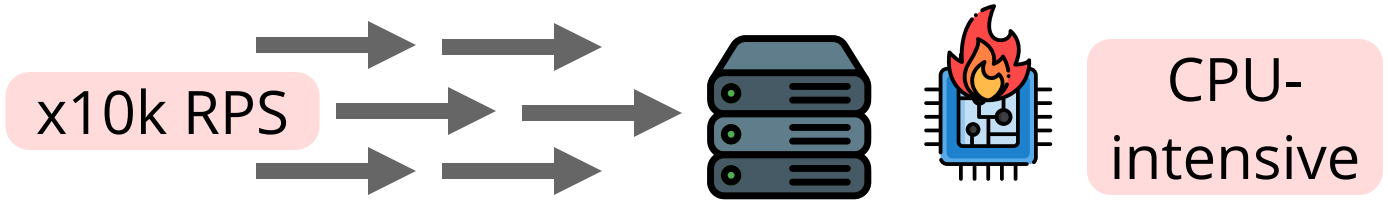

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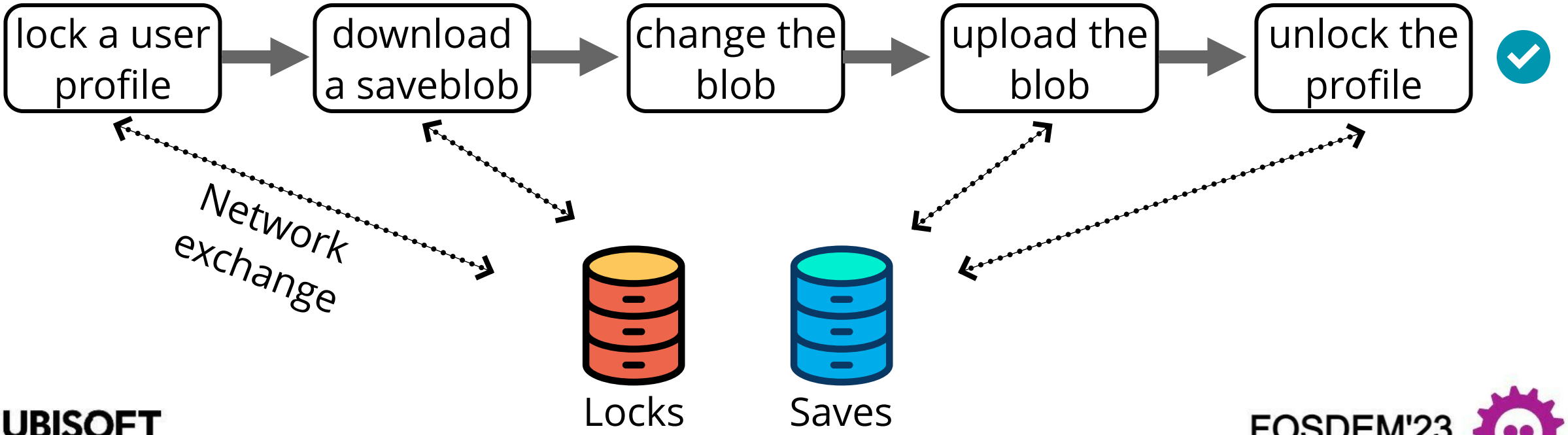


Trivial scheduler problems

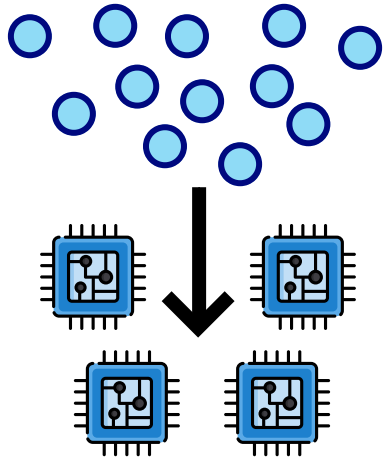
Won't scale

Trivial scheduler problems

Won't scale

Need multiple threads

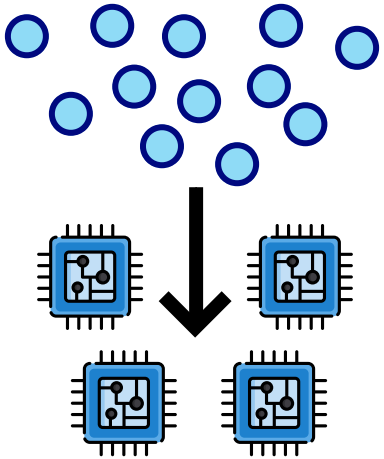
Choking on CPU



Trivial scheduler problems

Won't scale

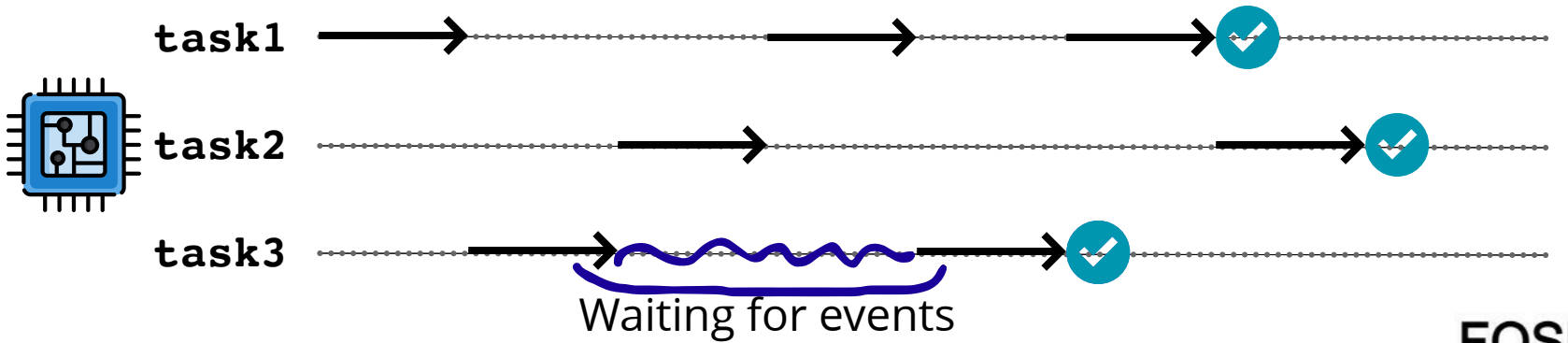
Need multiple threads



Choking on CPU

Can't postpone a blocked task

Need coroutines



Trivial scheduler v2

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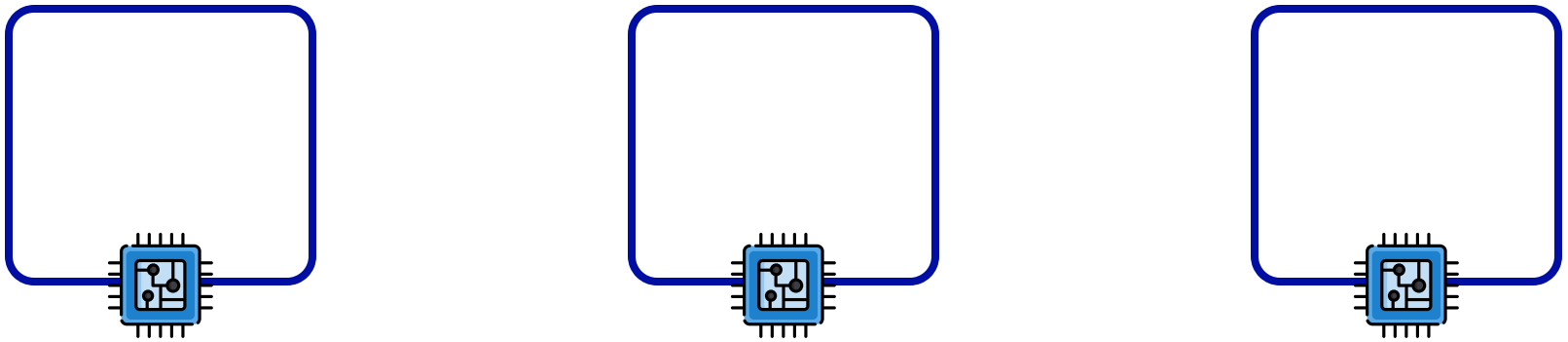
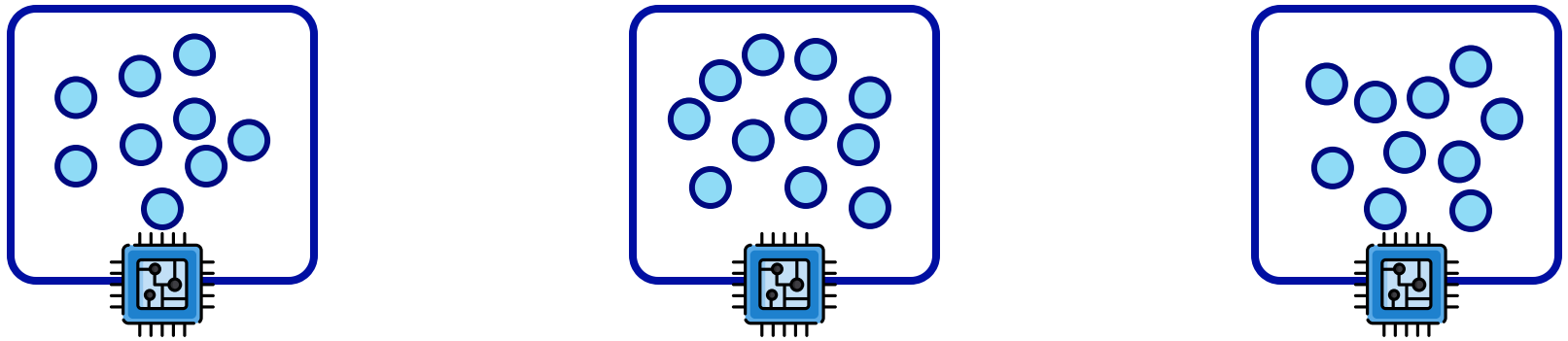


Thread pool

Trivial scheduler v2

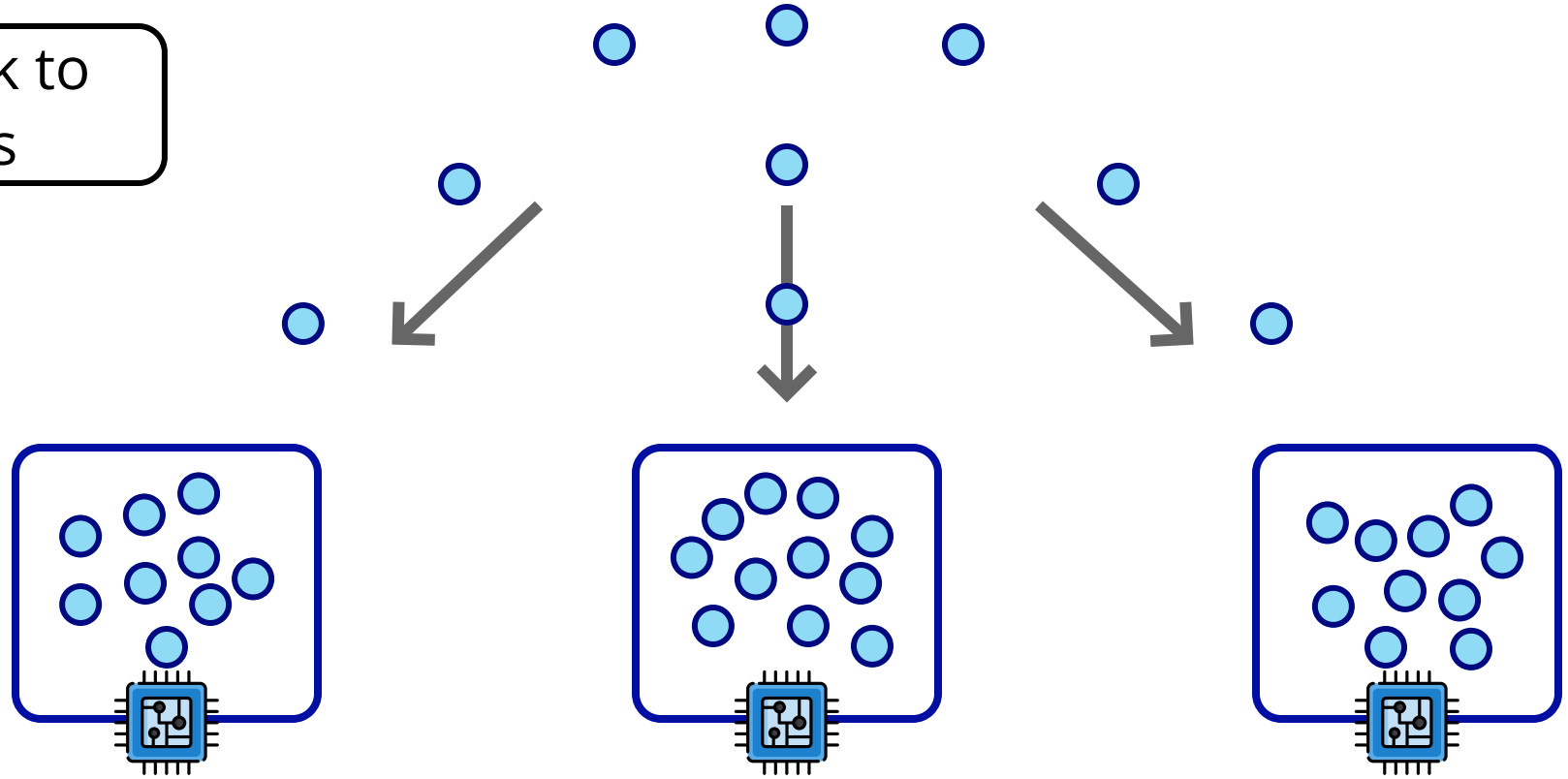
Tasks stick to threads



Trivial scheduler v2

Round-robin distribution

Tasks stick to threads

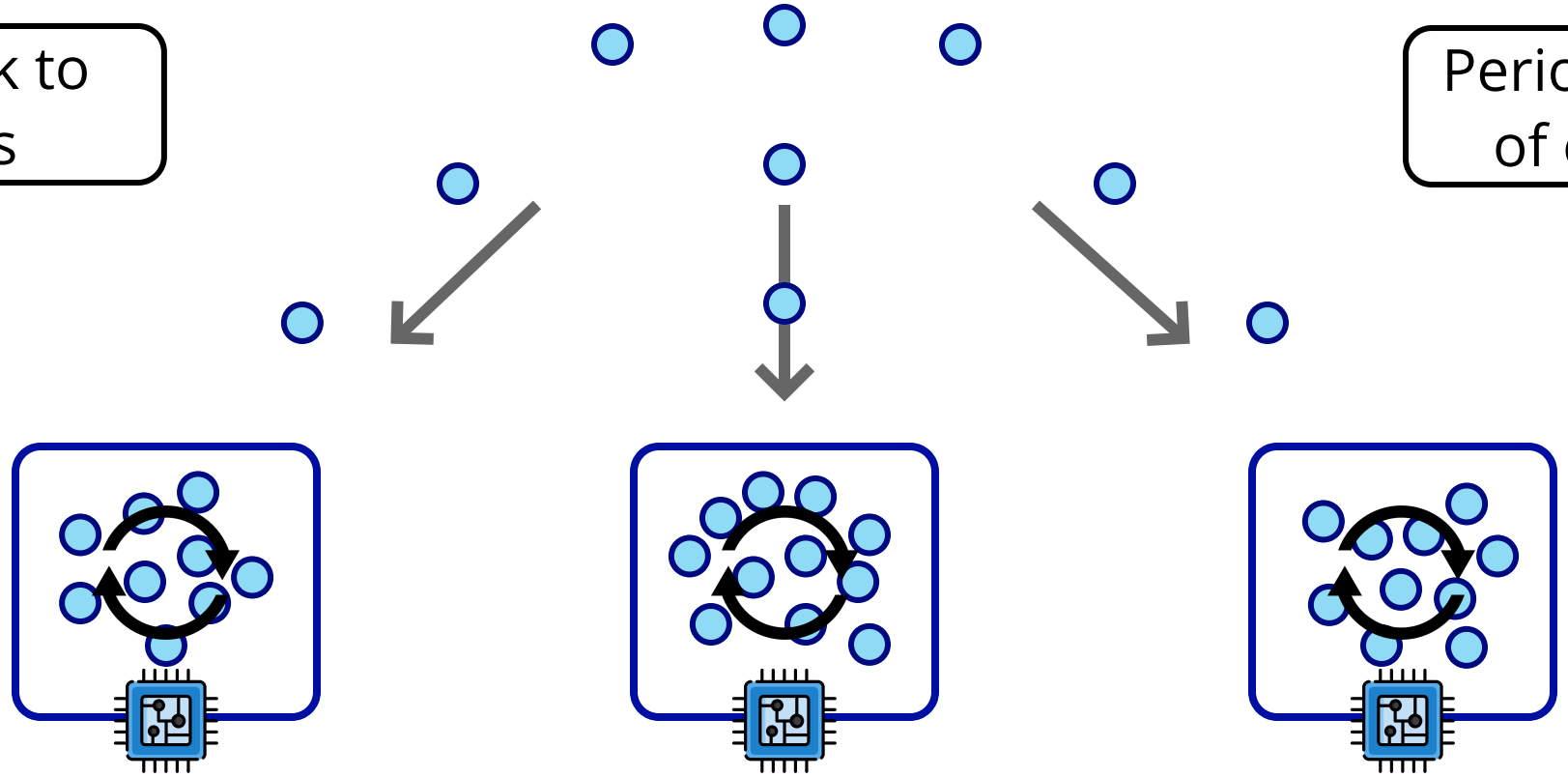


Trivial scheduler v2

Round-robin distribution

Tasks stick to threads

Periodic update of each task



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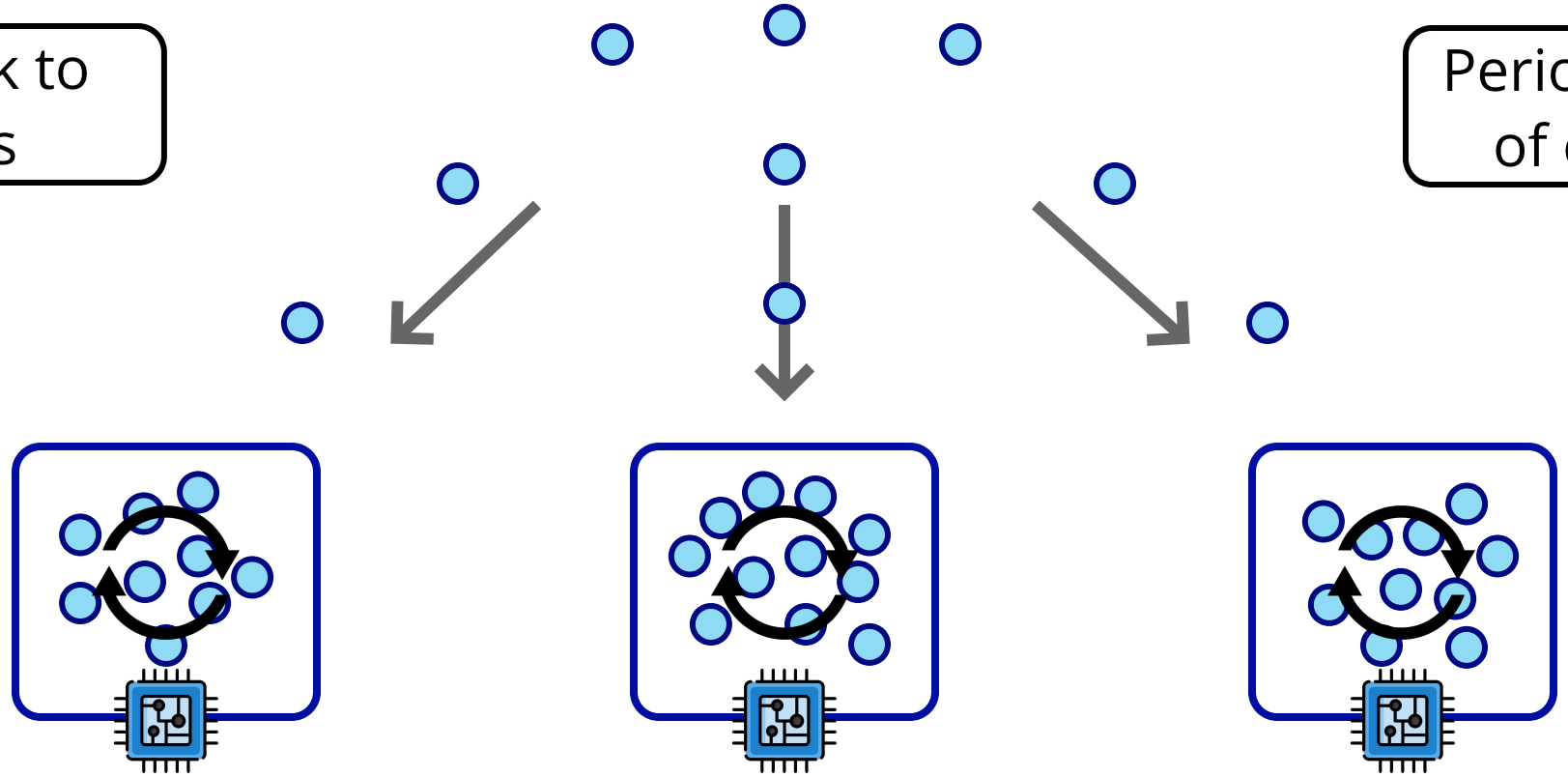
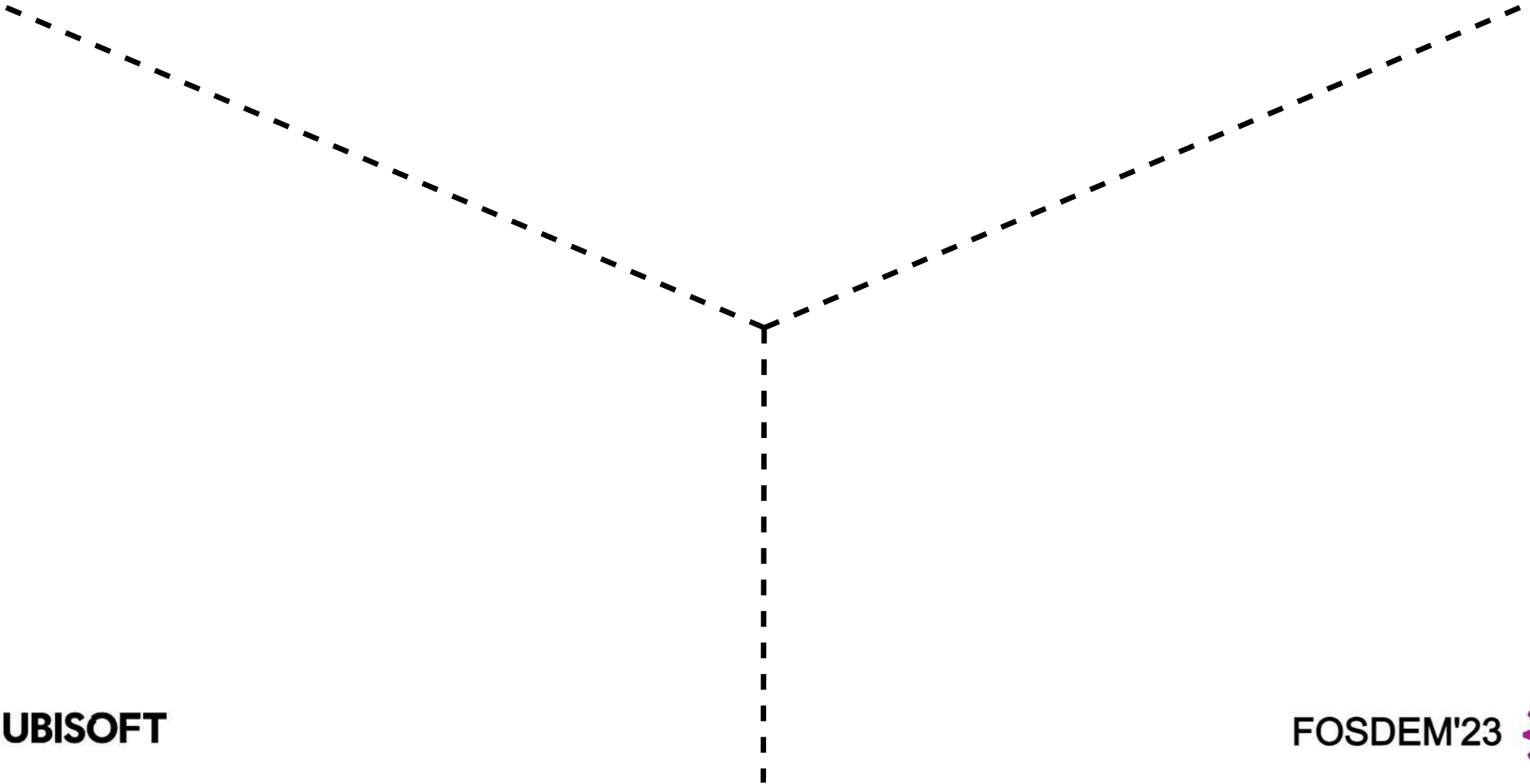


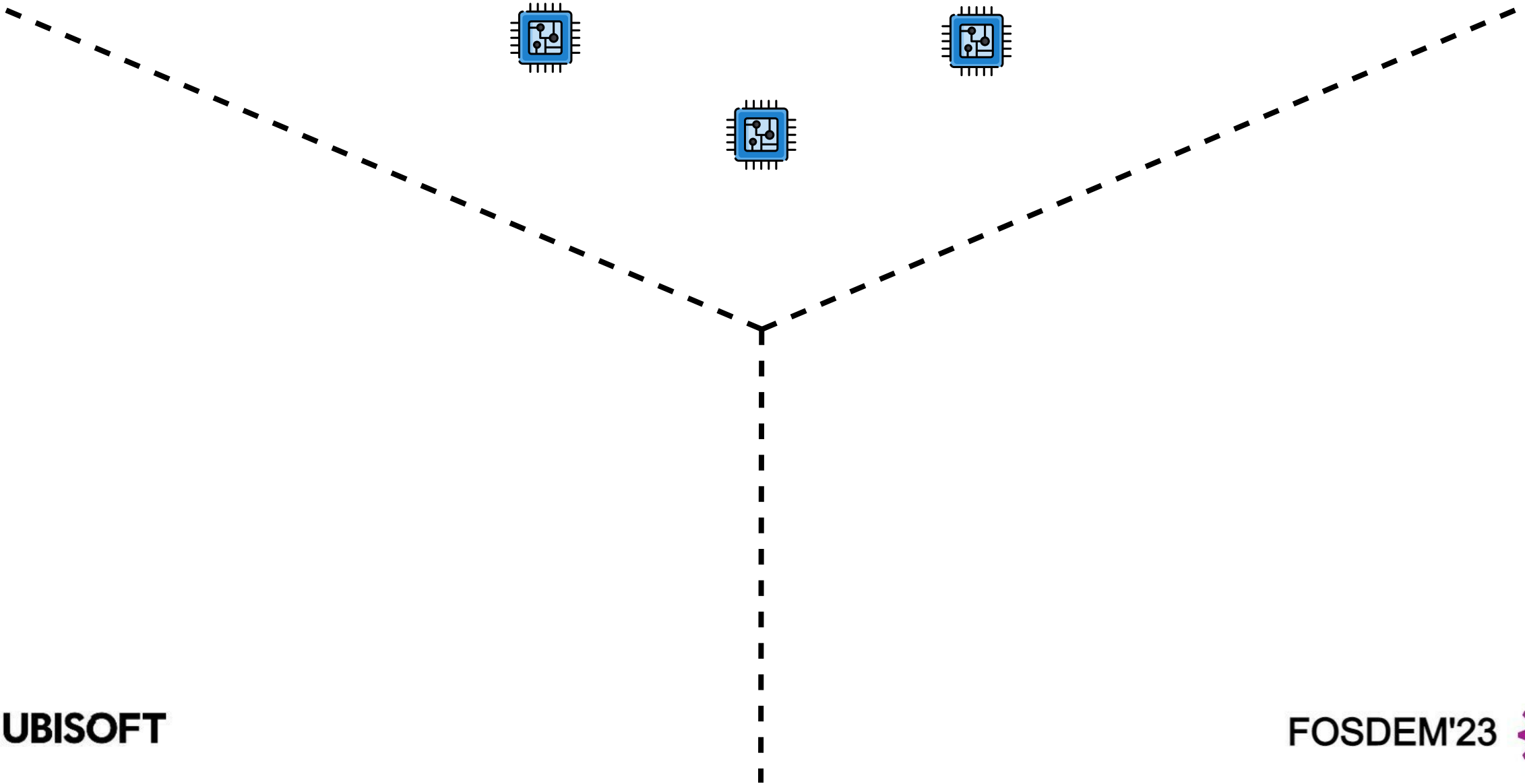
Updater "updates" all tasks all the time

Trivial scheduler v2 problems



Trivial scheduler v2 problems

Uneven CPU usage



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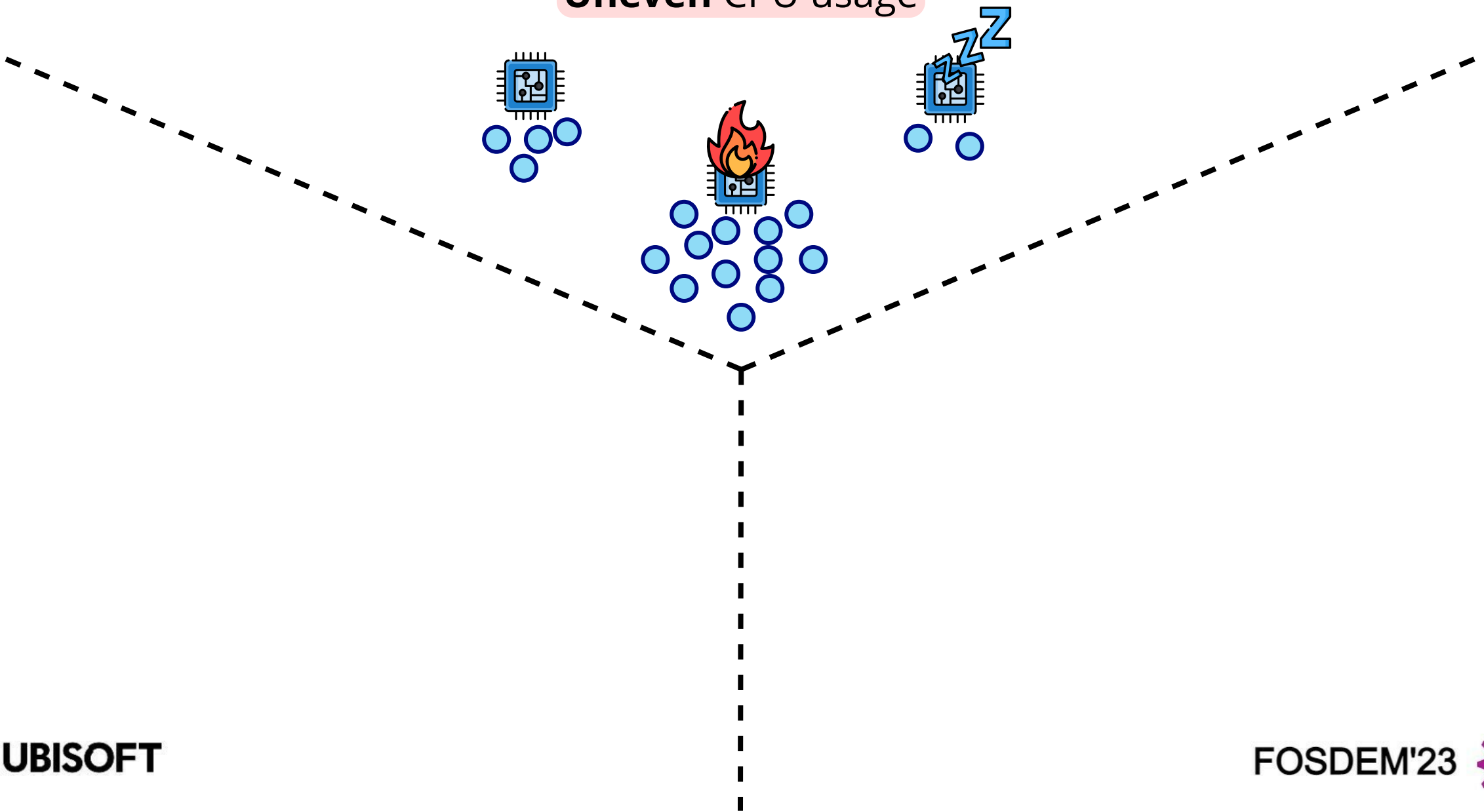

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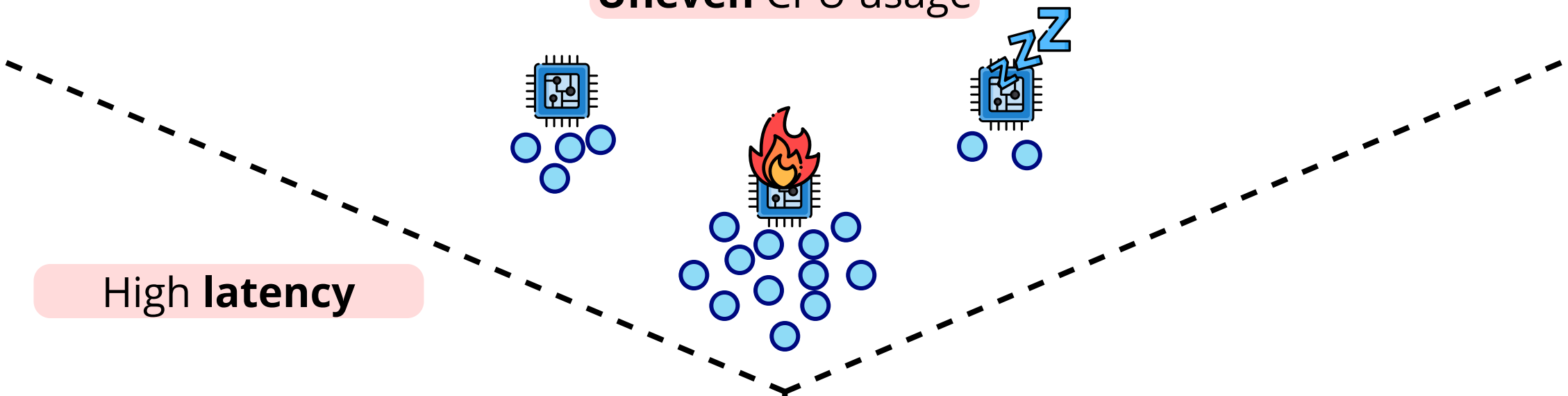
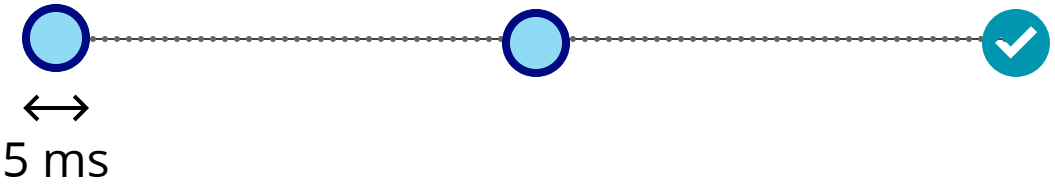


High **latency**



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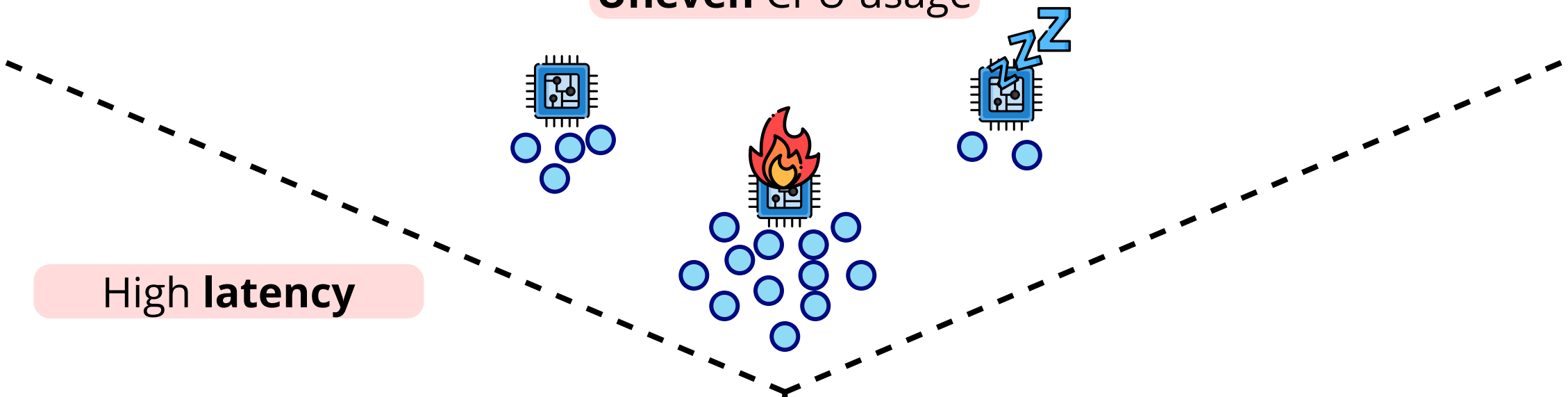

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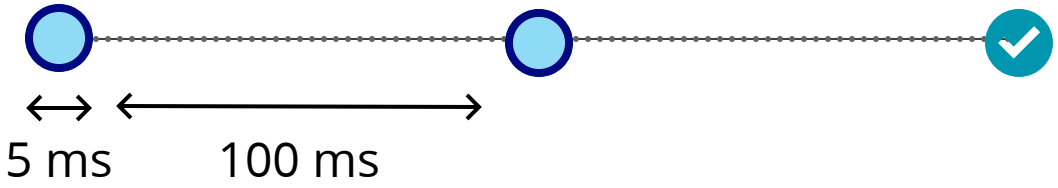
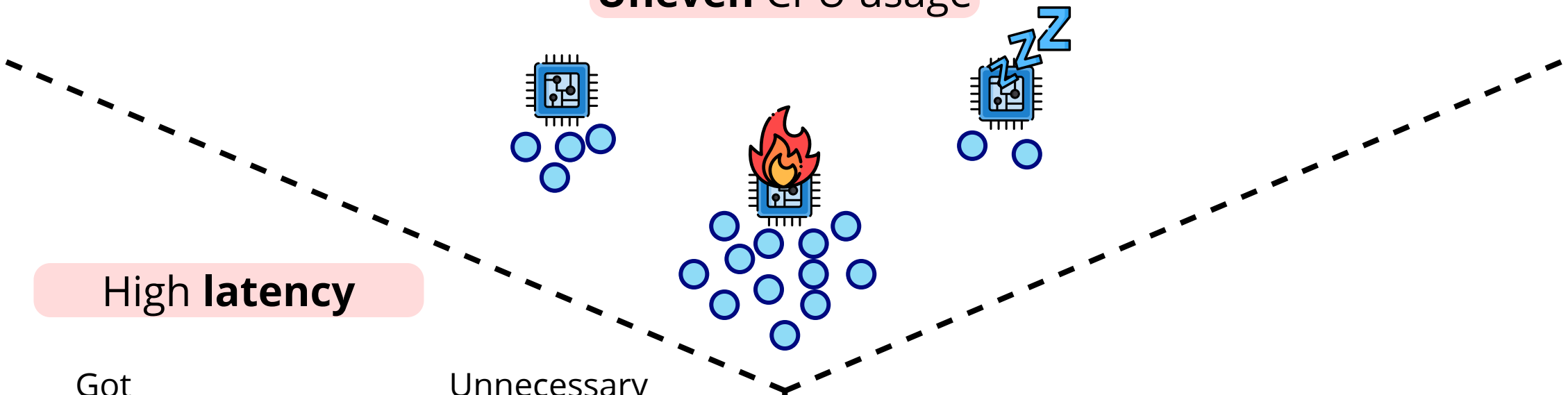


Min latency is **215 ms**

Trivial scheduler v2 problems

Uneven CPU usage



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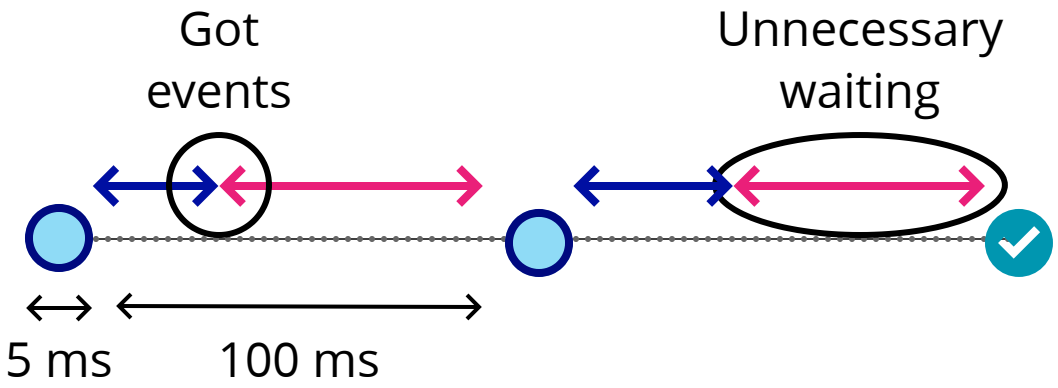

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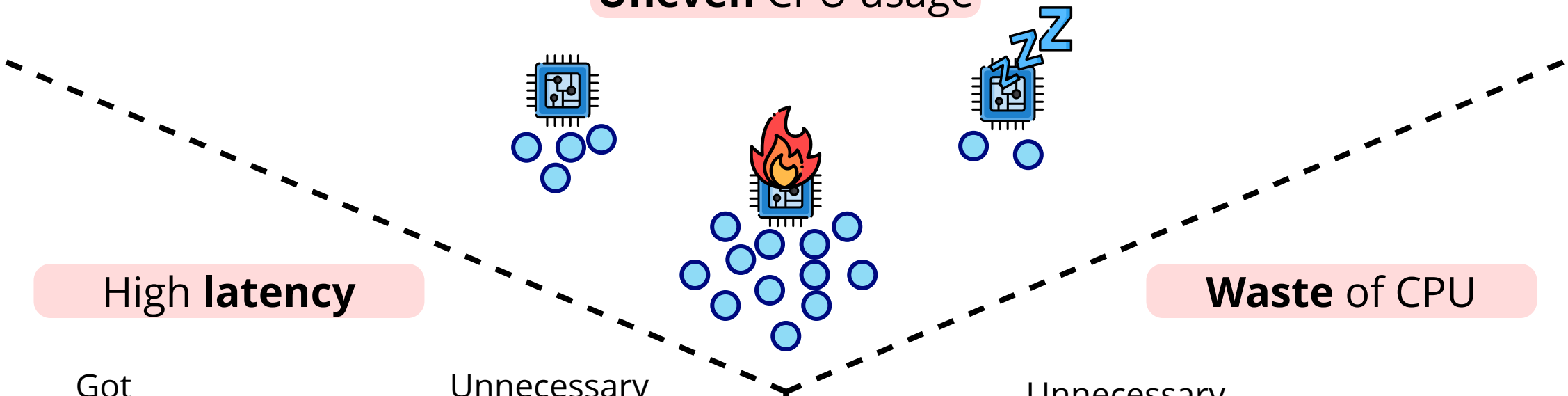

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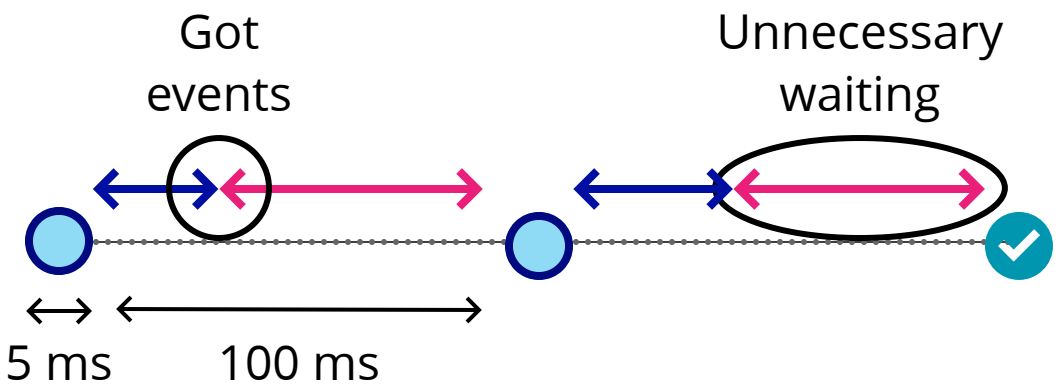

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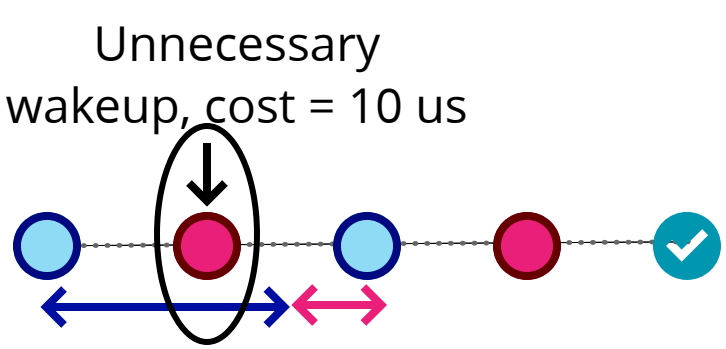
Waste of CPU



x10 000 tasks =
100 ms wasted

Summary requirements

Summary requirements

Fairness

Summary requirements

Fairness

Coroutines

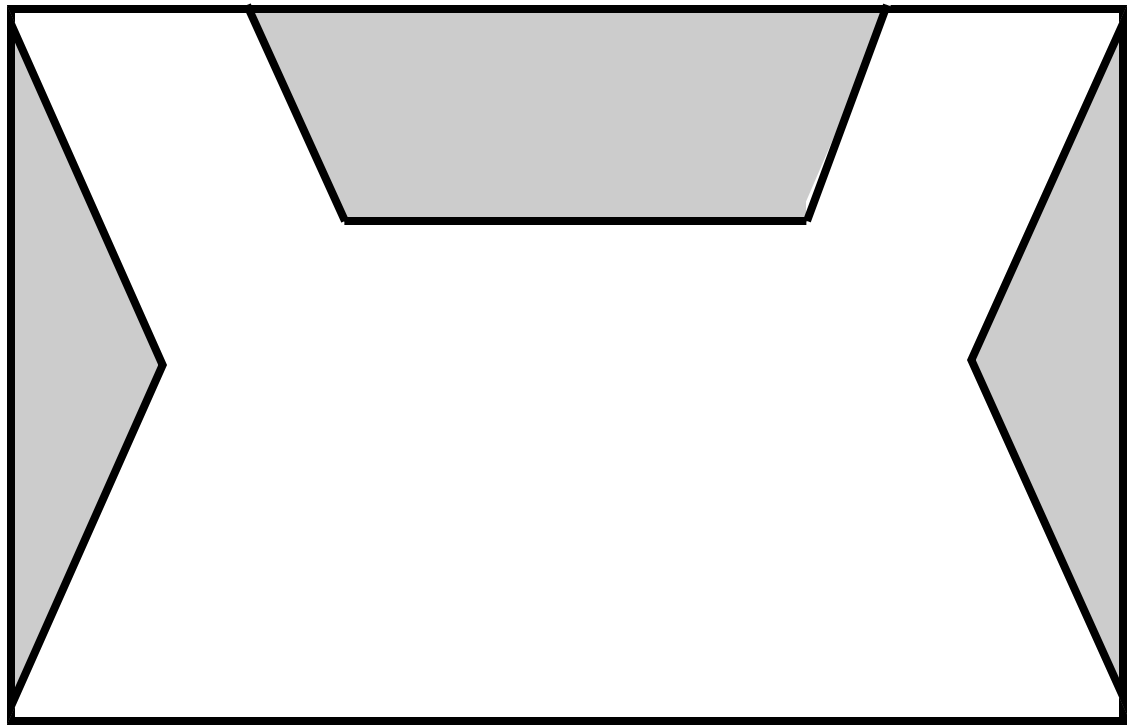
Summary requirements

Fairness

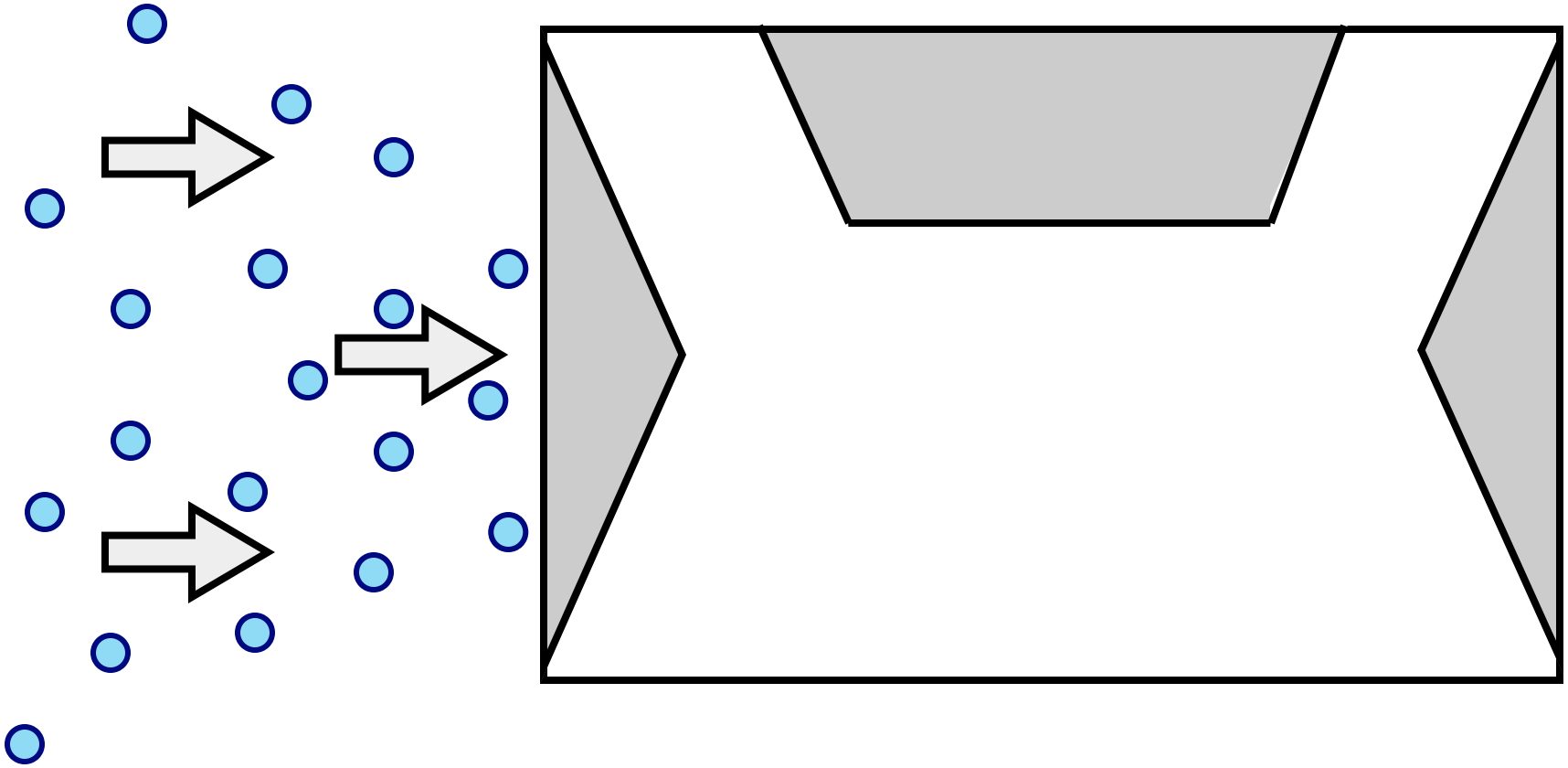
Coroutines

Events

TaskScheduler



TaskScheduler



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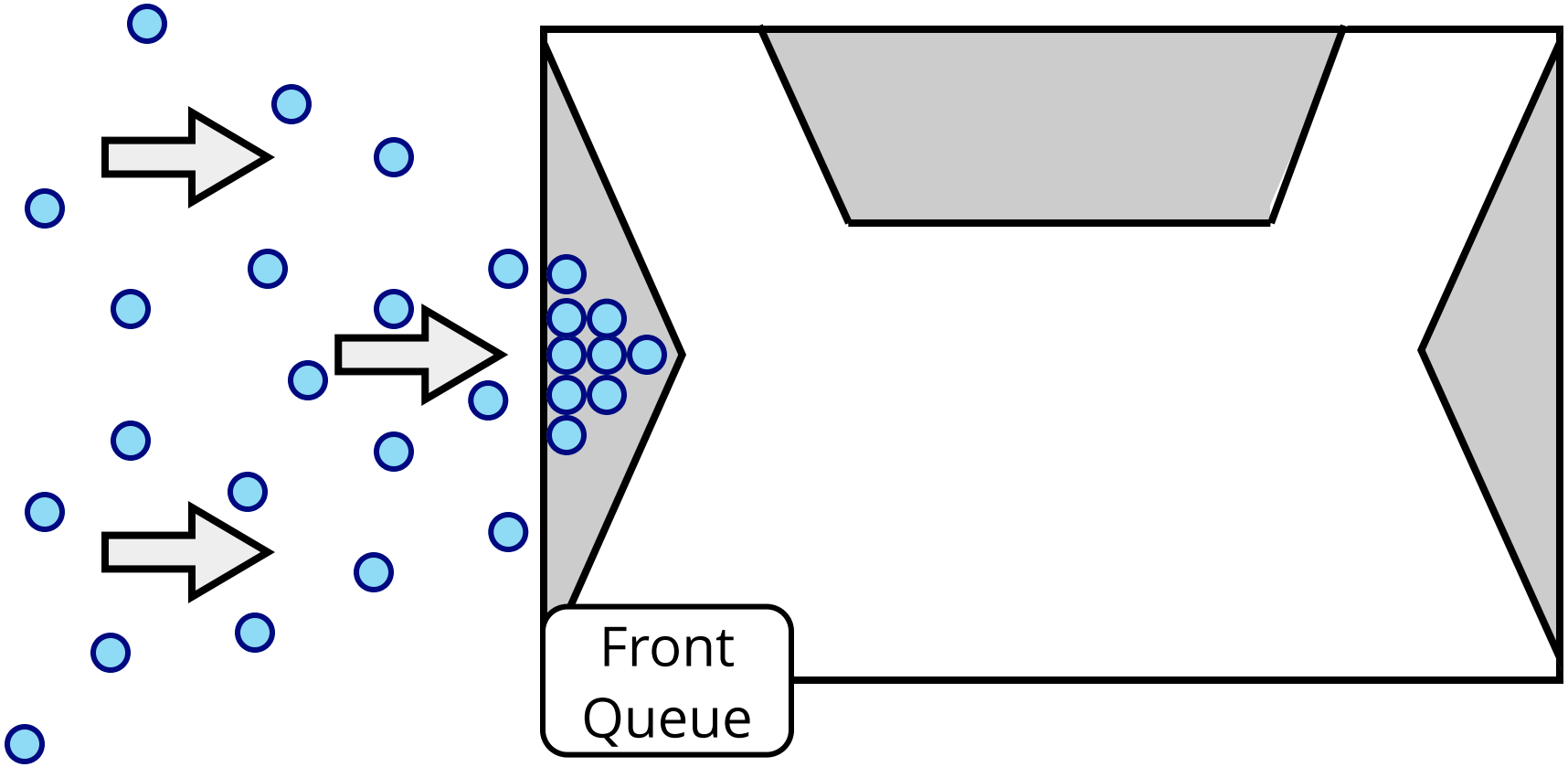

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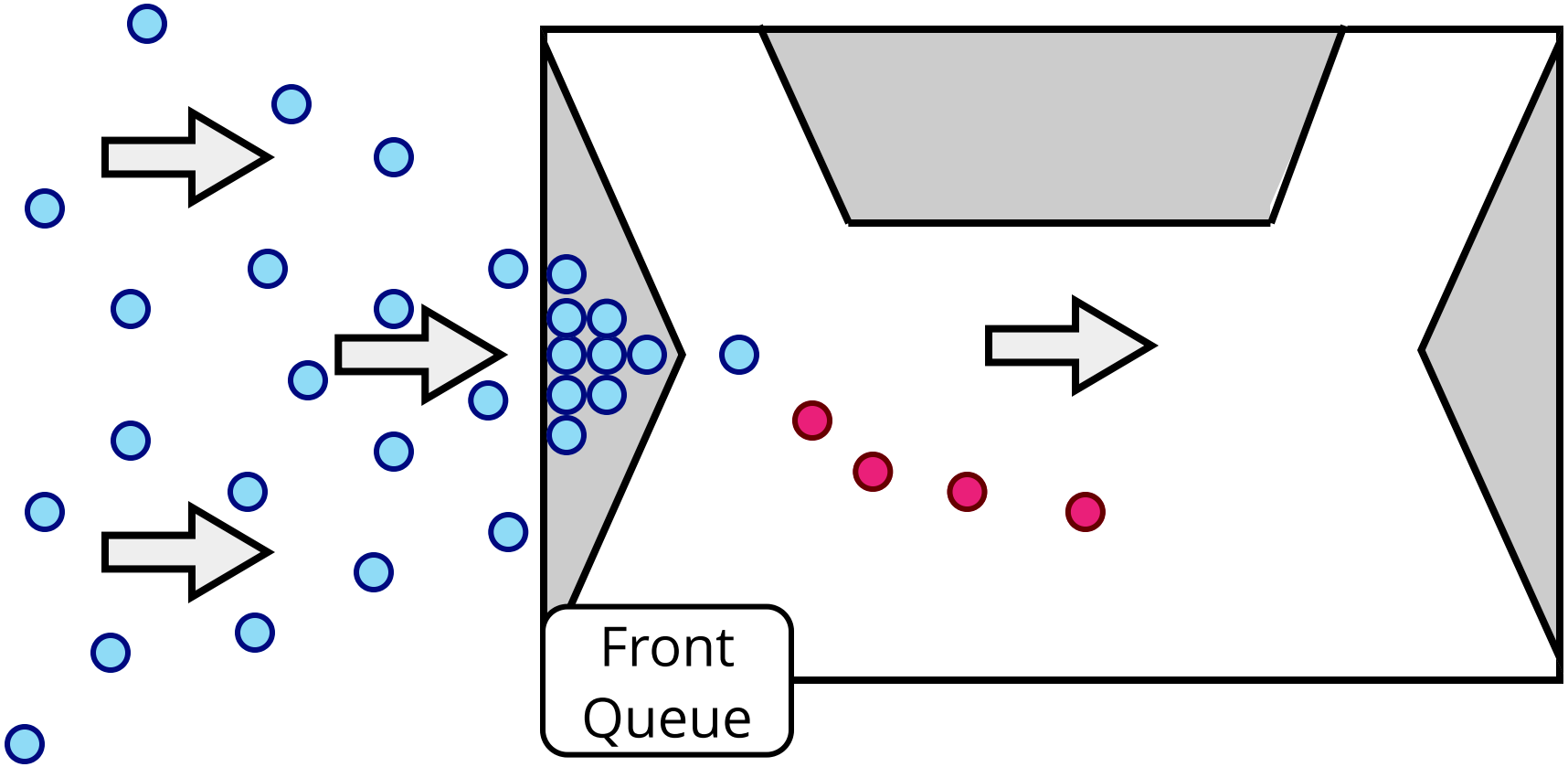

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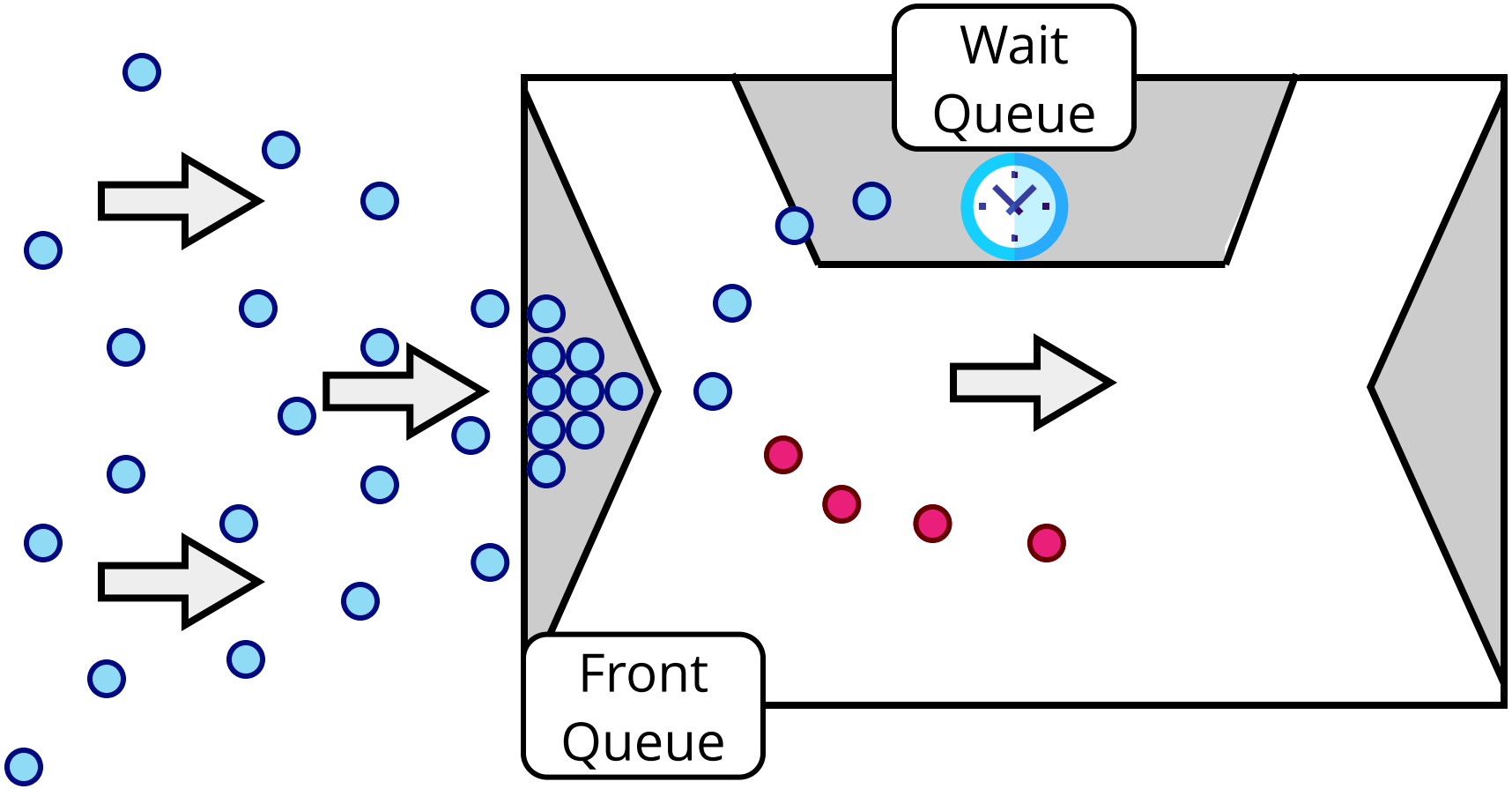

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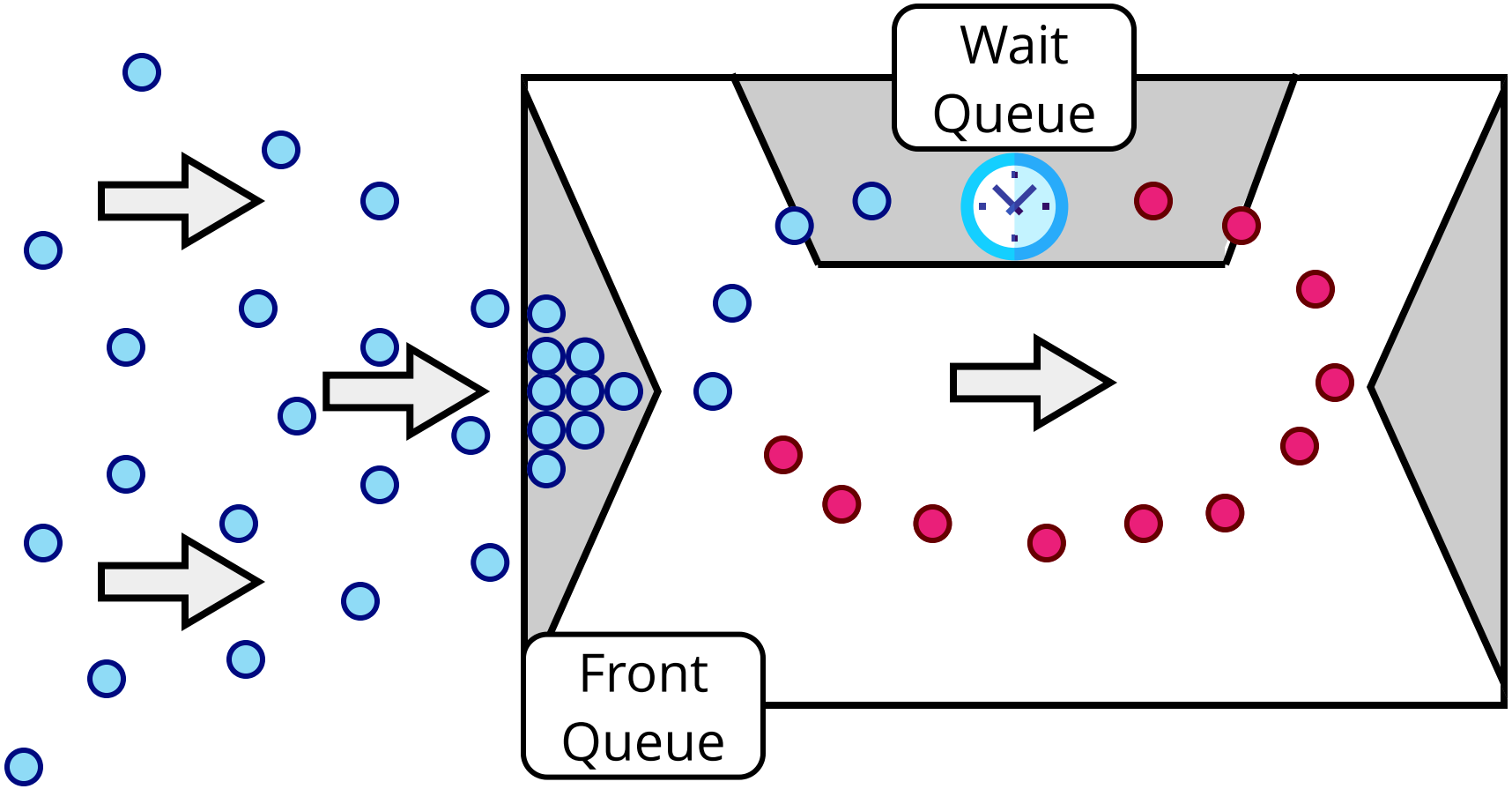
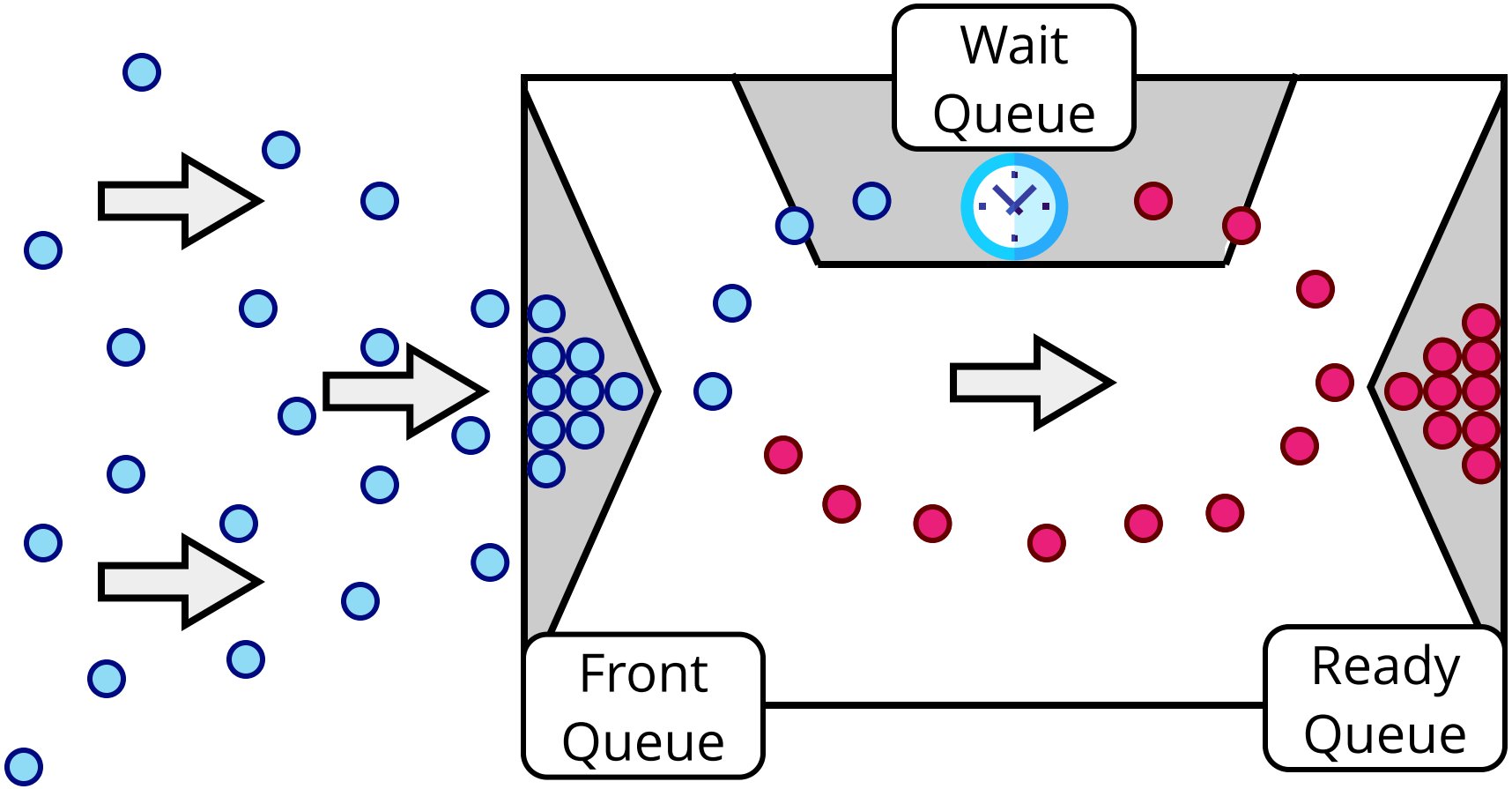


TaskScheduler



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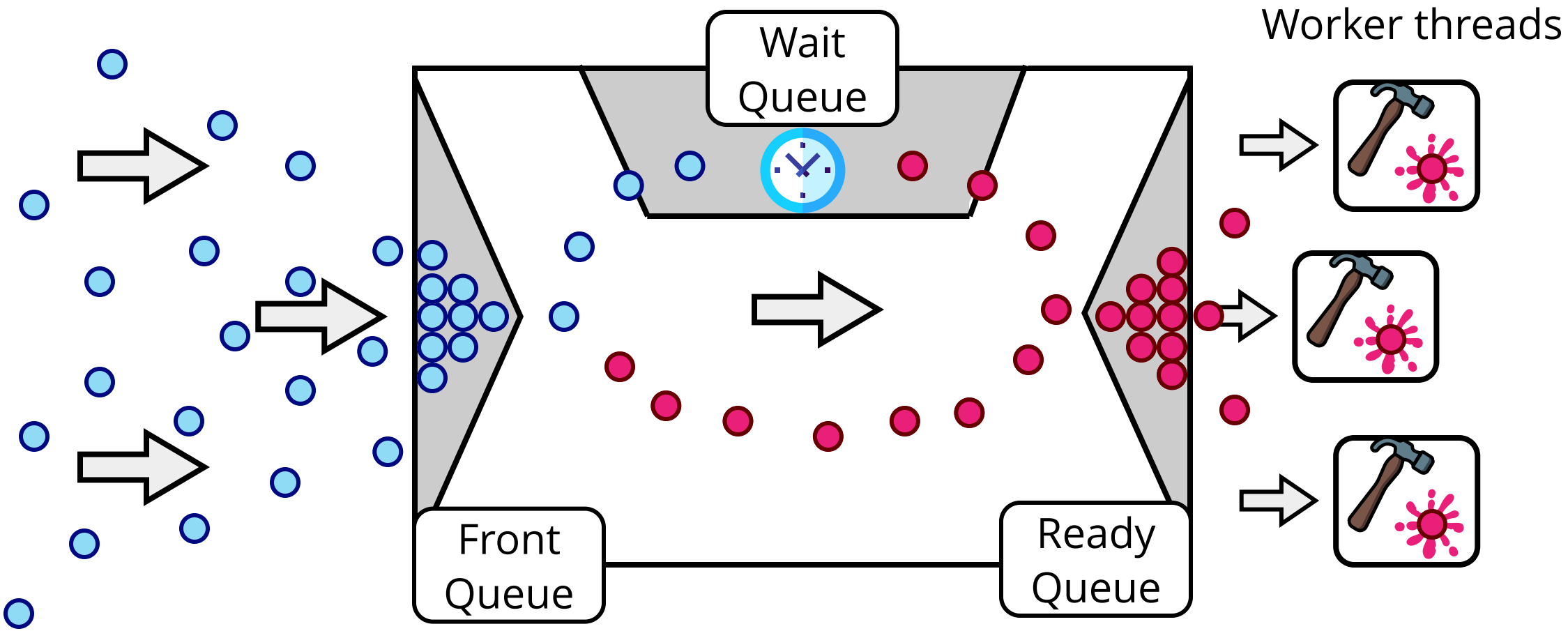

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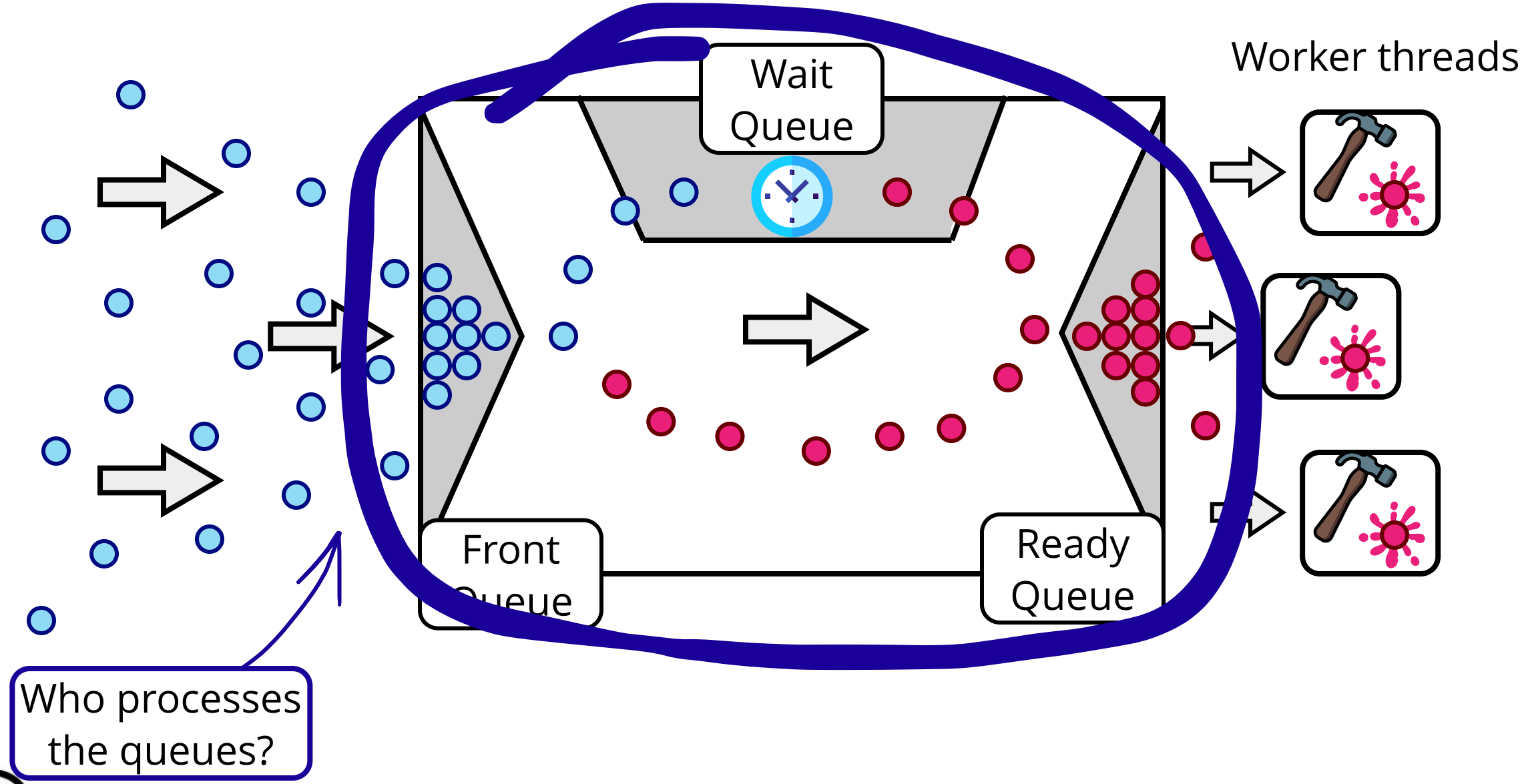

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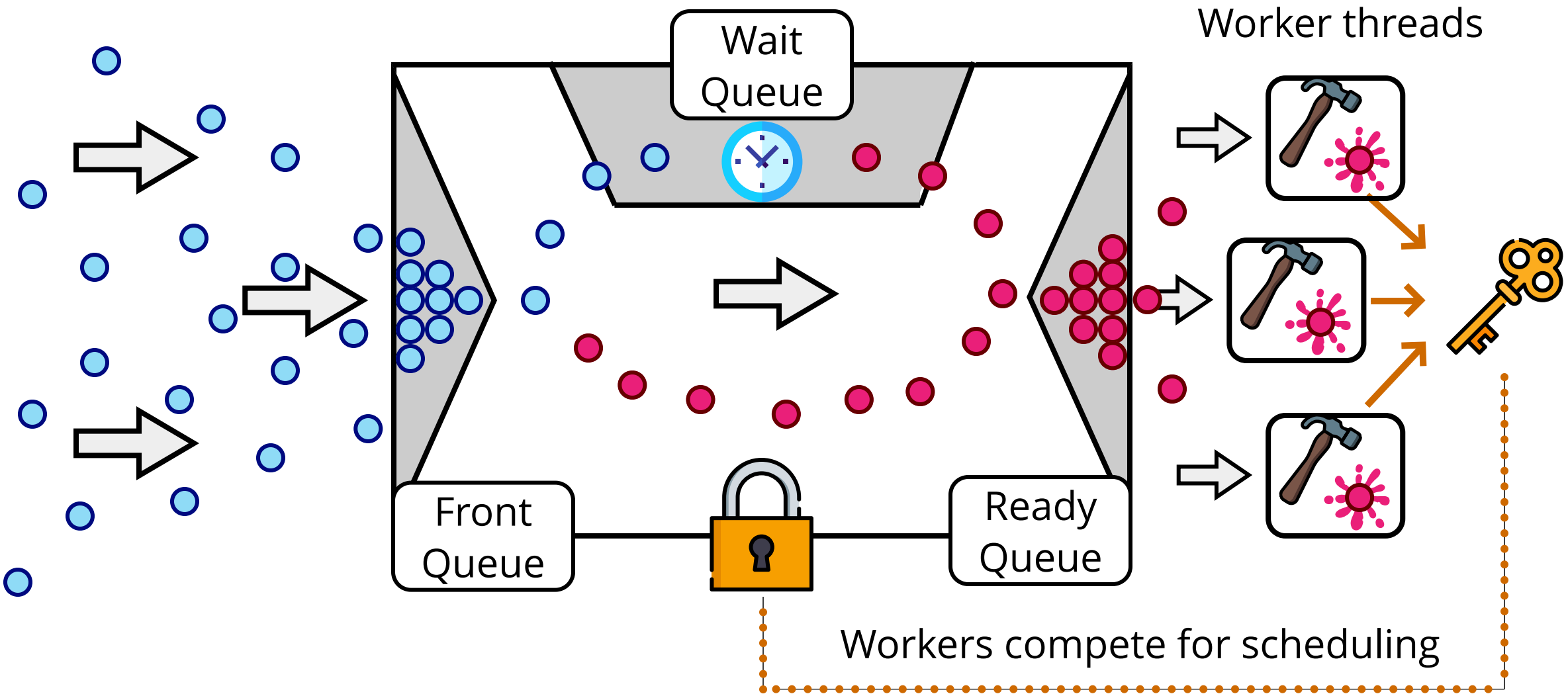
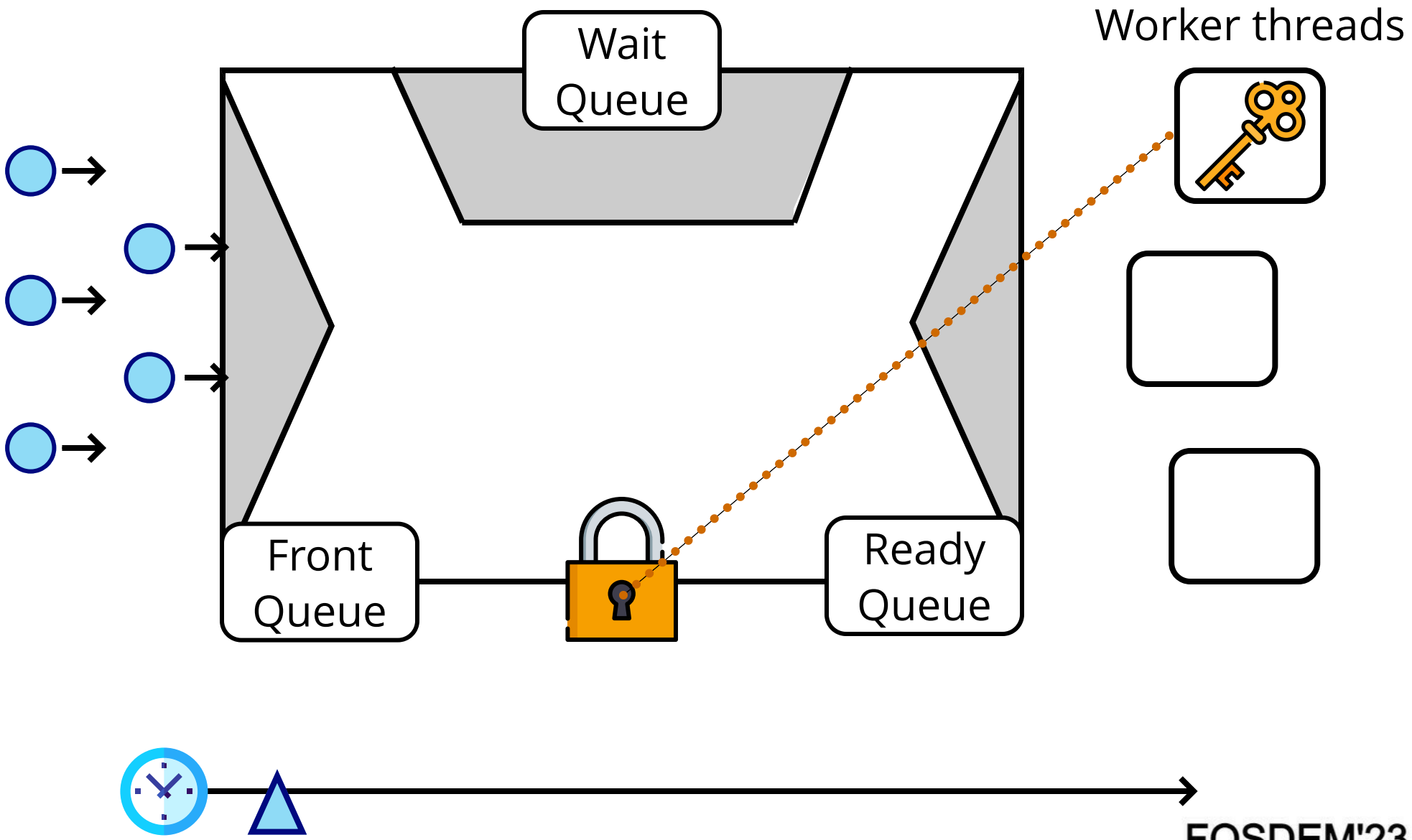
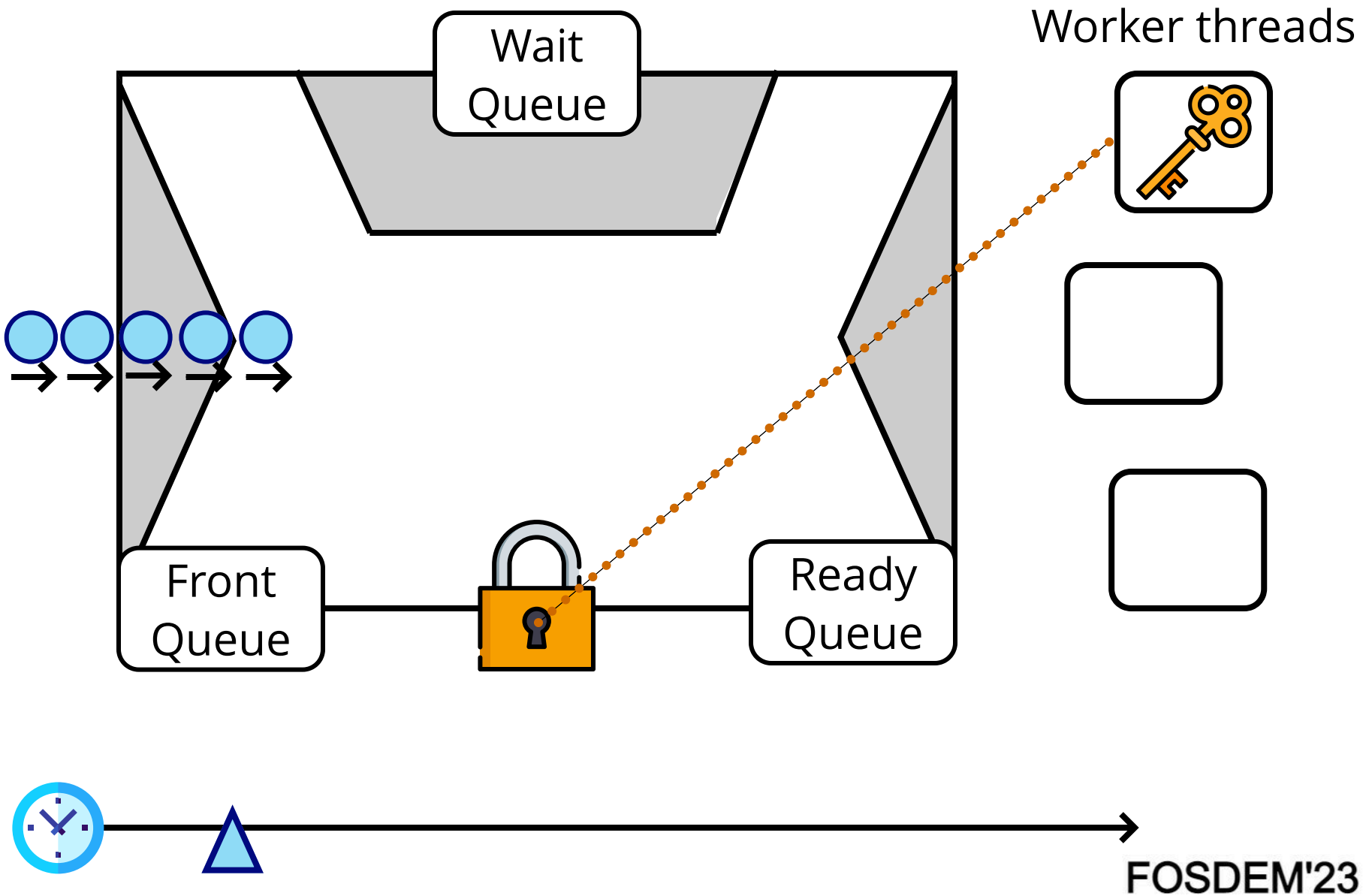


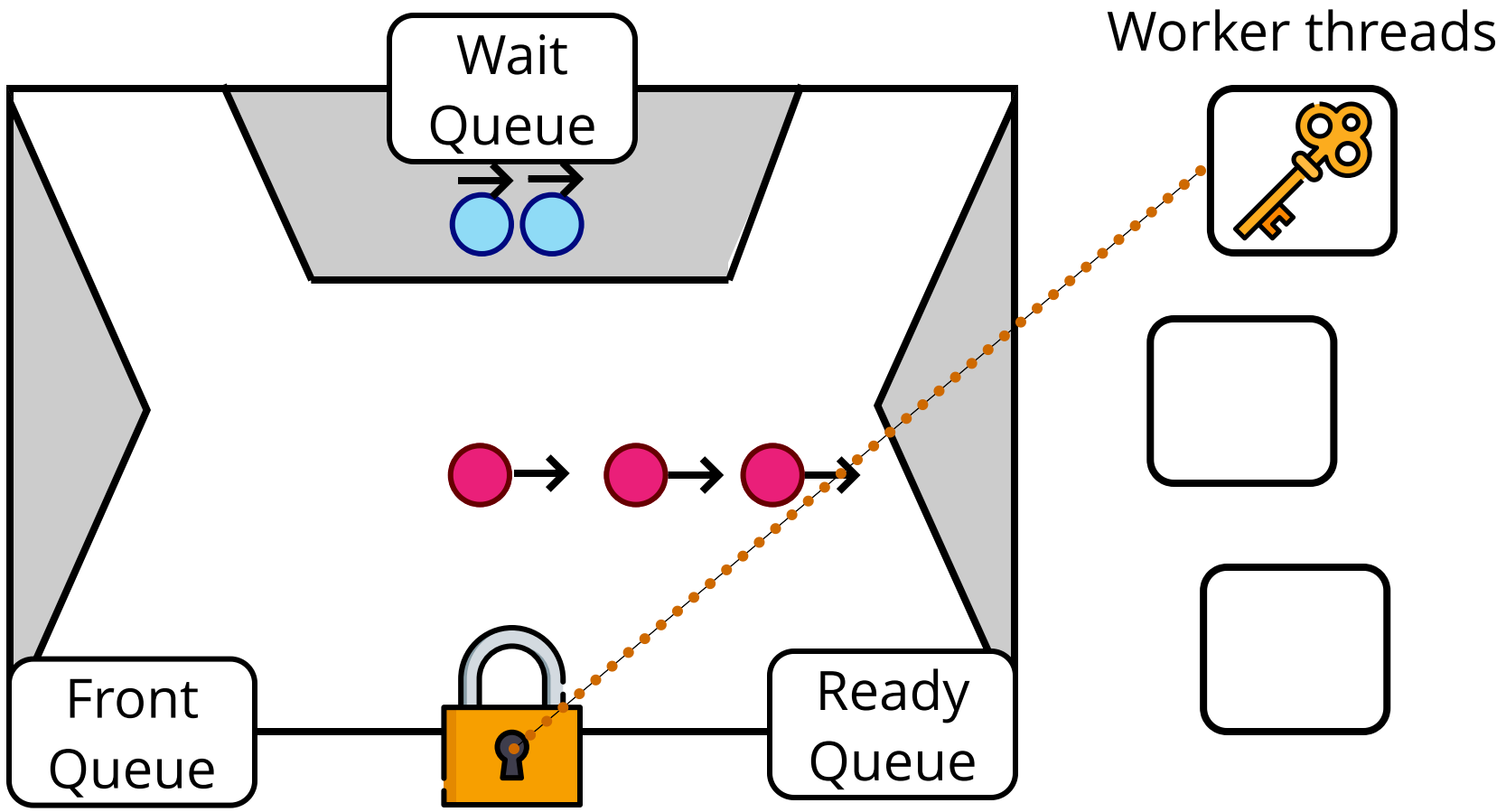
TaskScheduler example



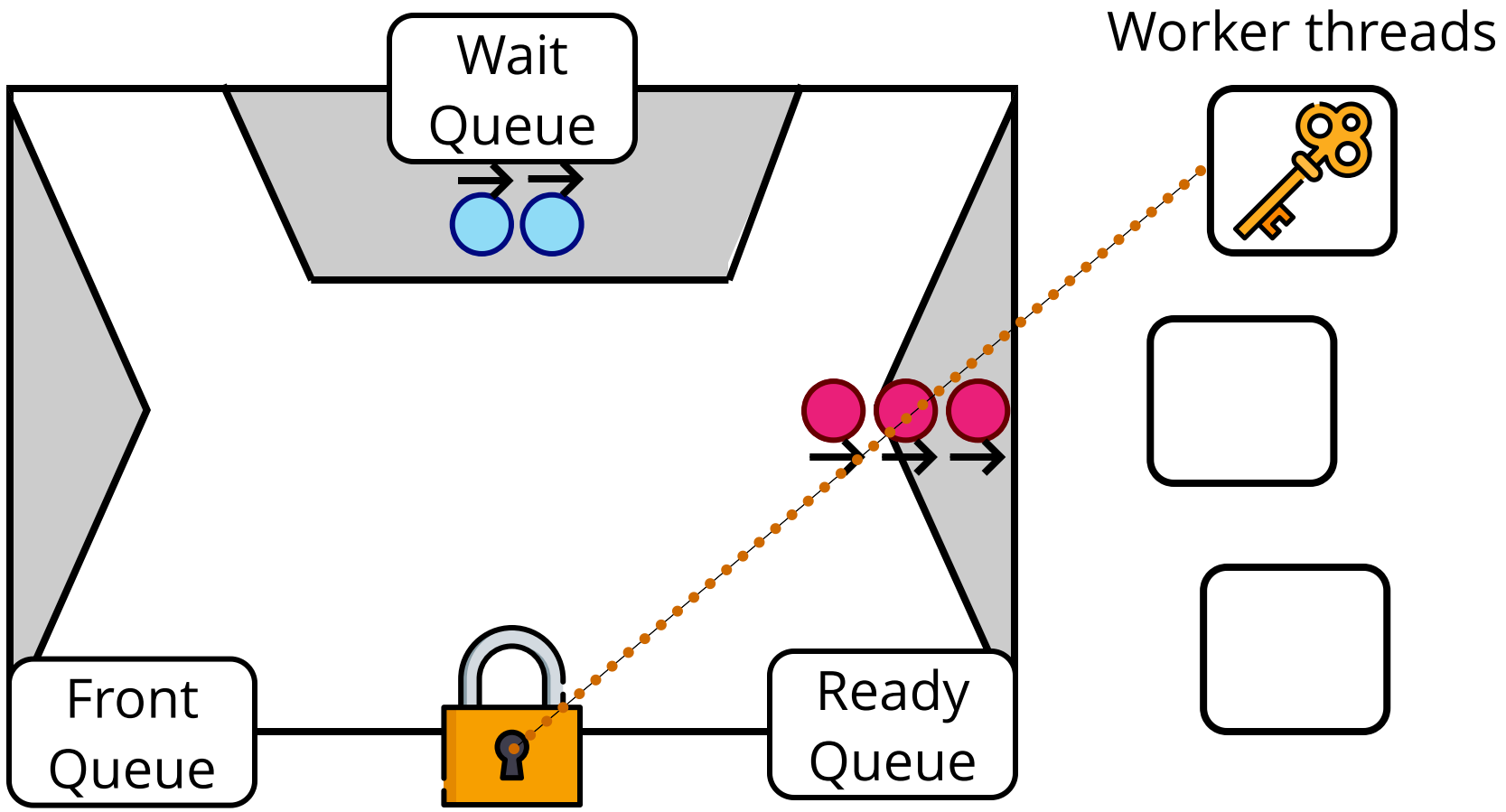
TaskScheduler



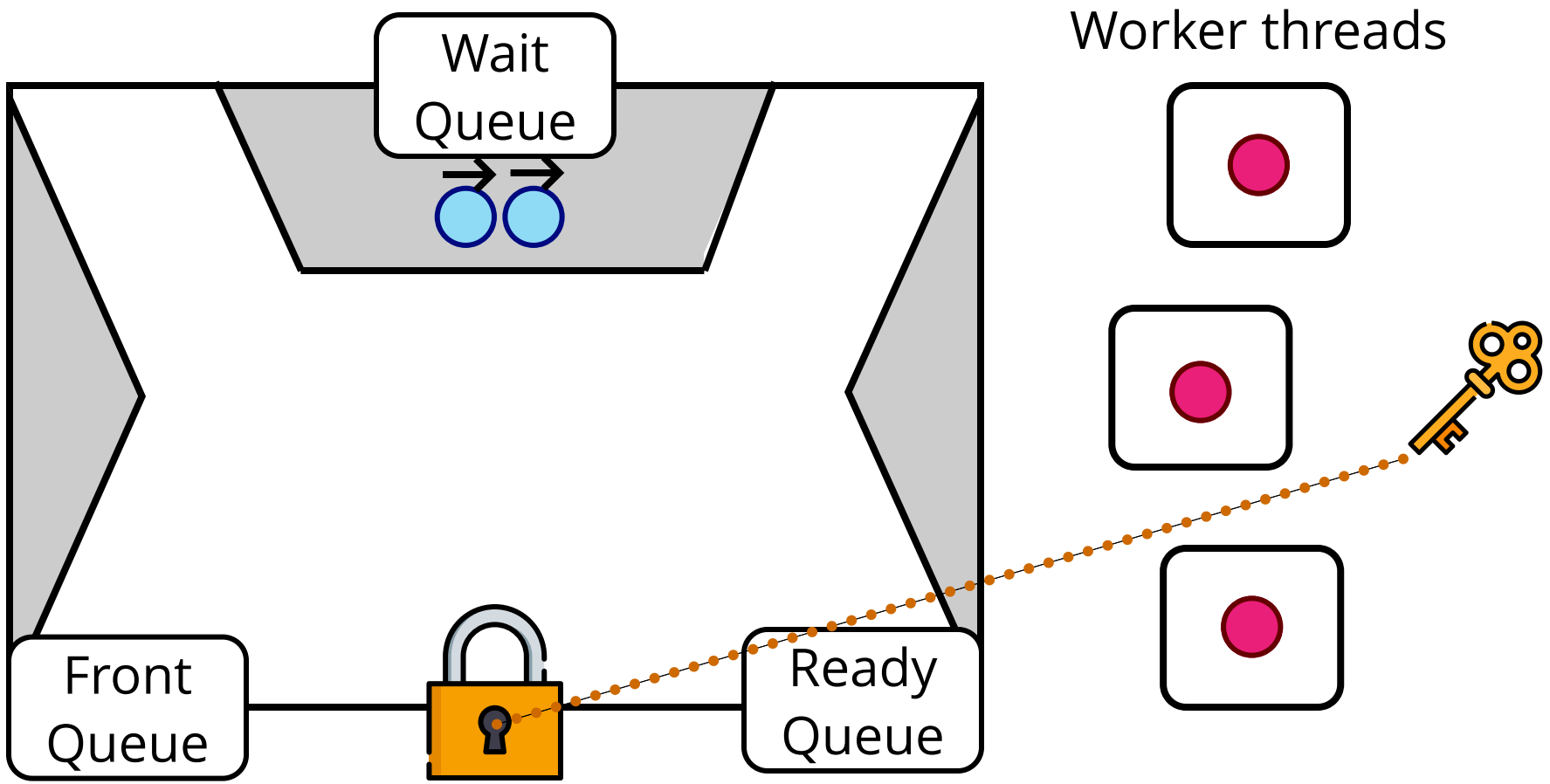
TaskScheduler



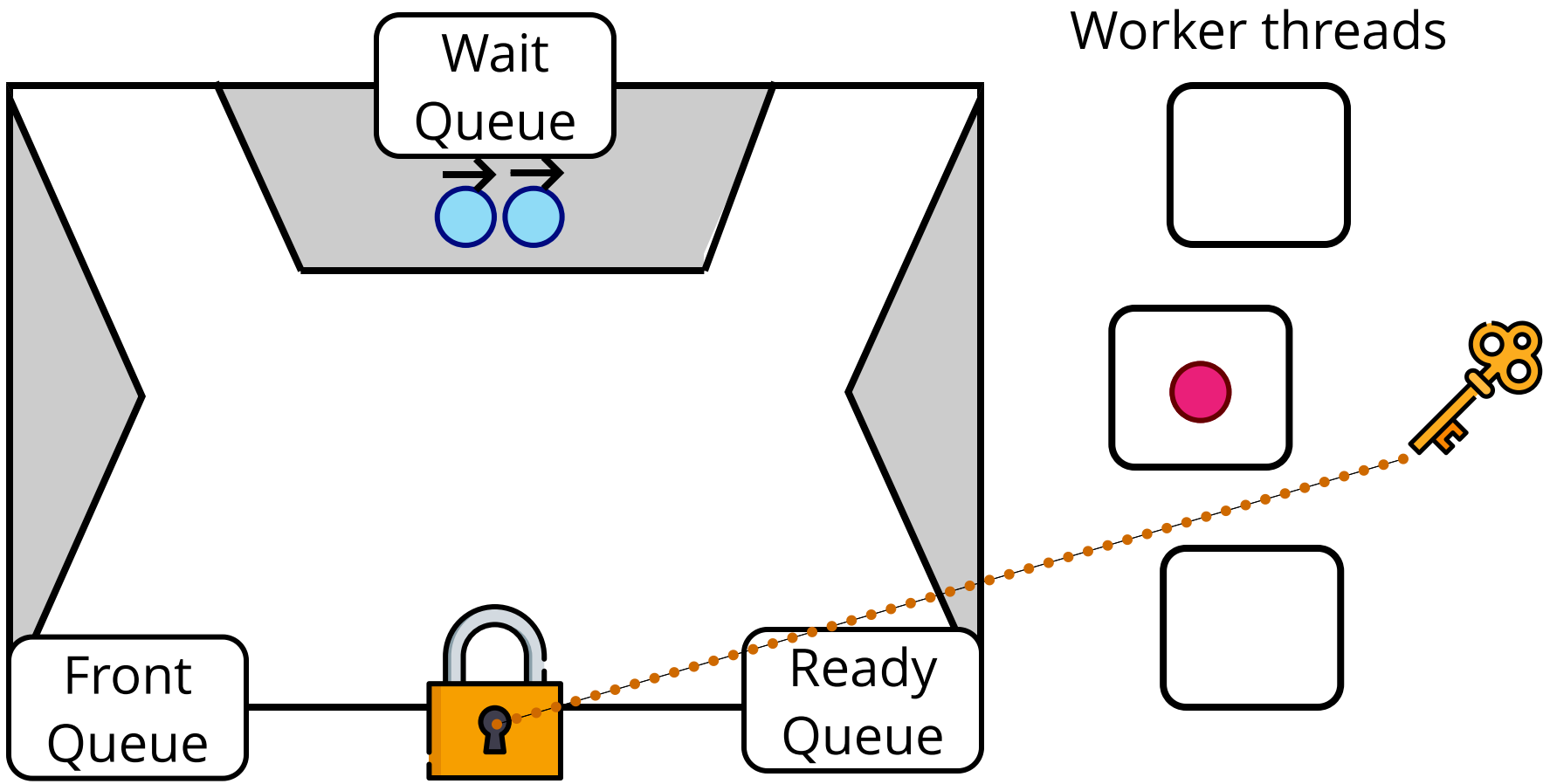
TaskScheduler



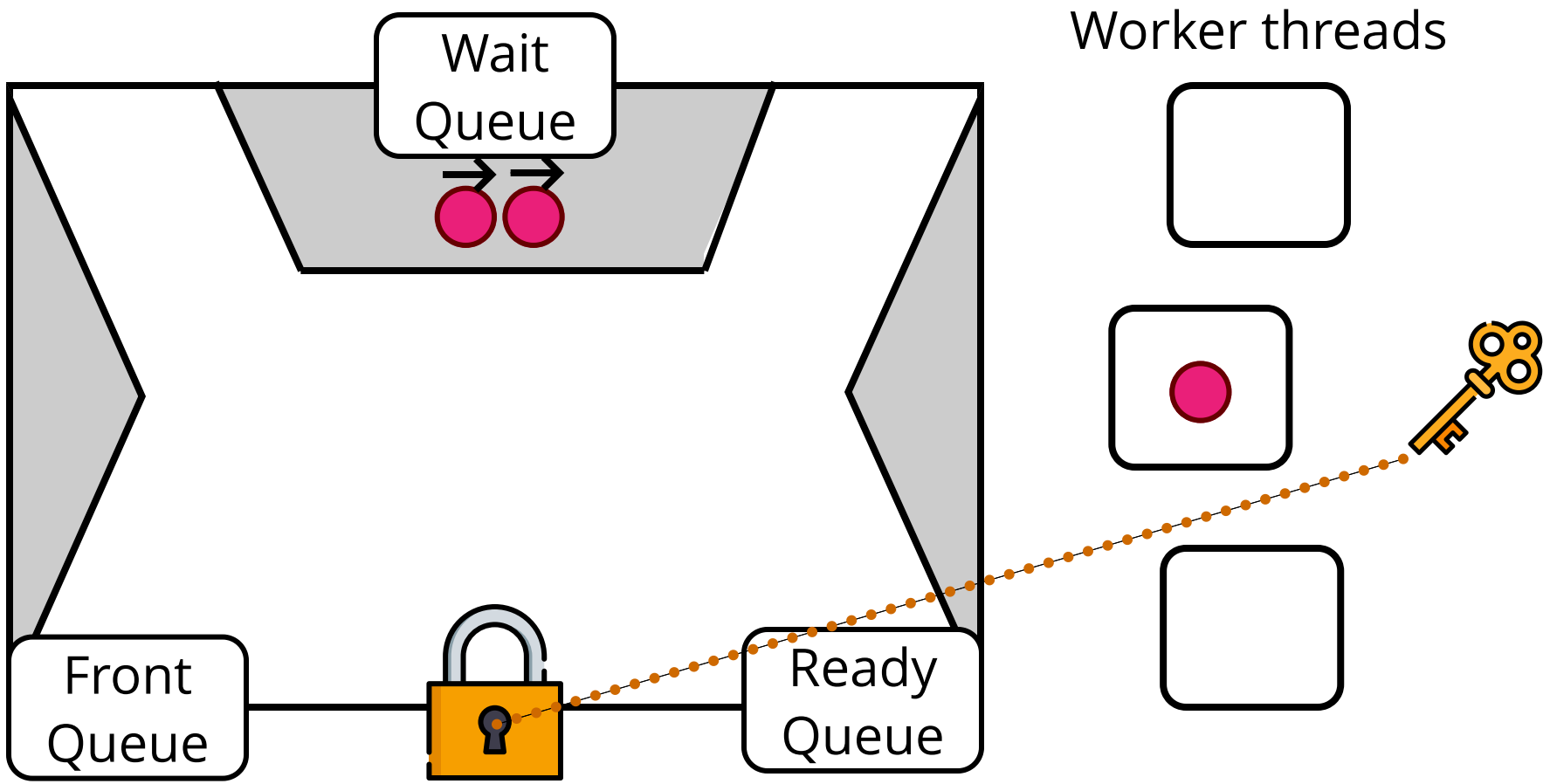
TaskScheduler



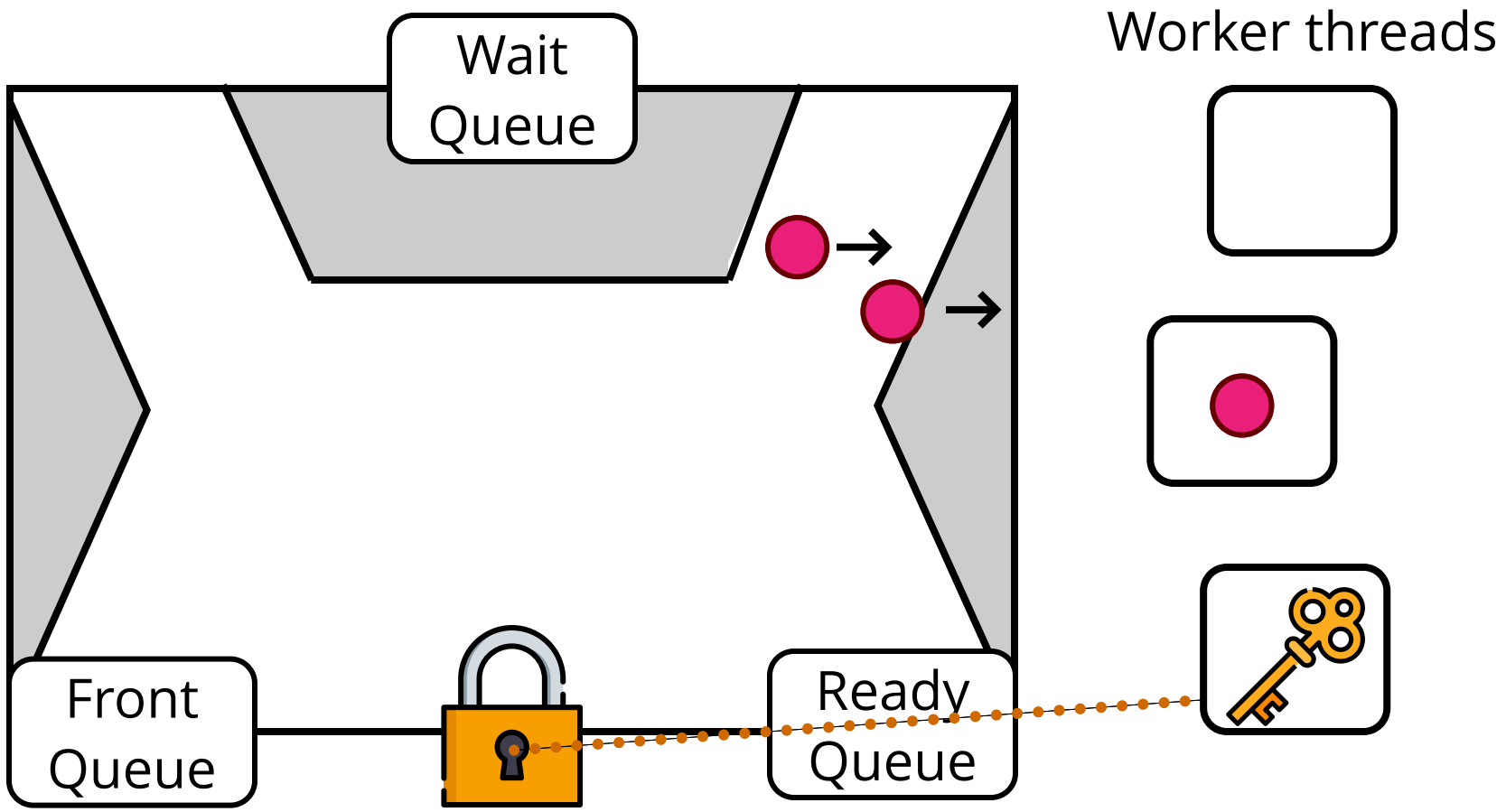
TaskScheduler



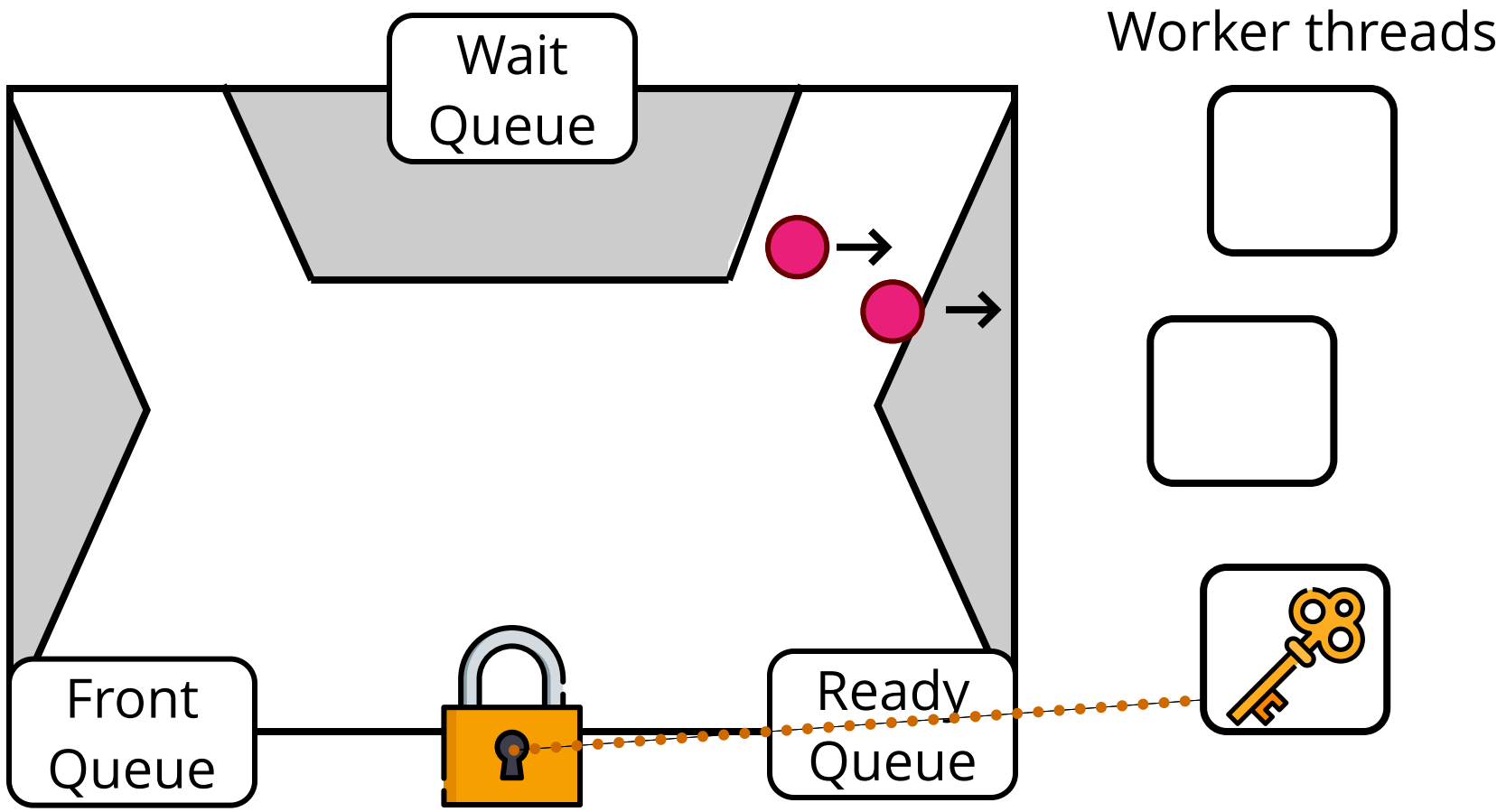
TaskScheduler



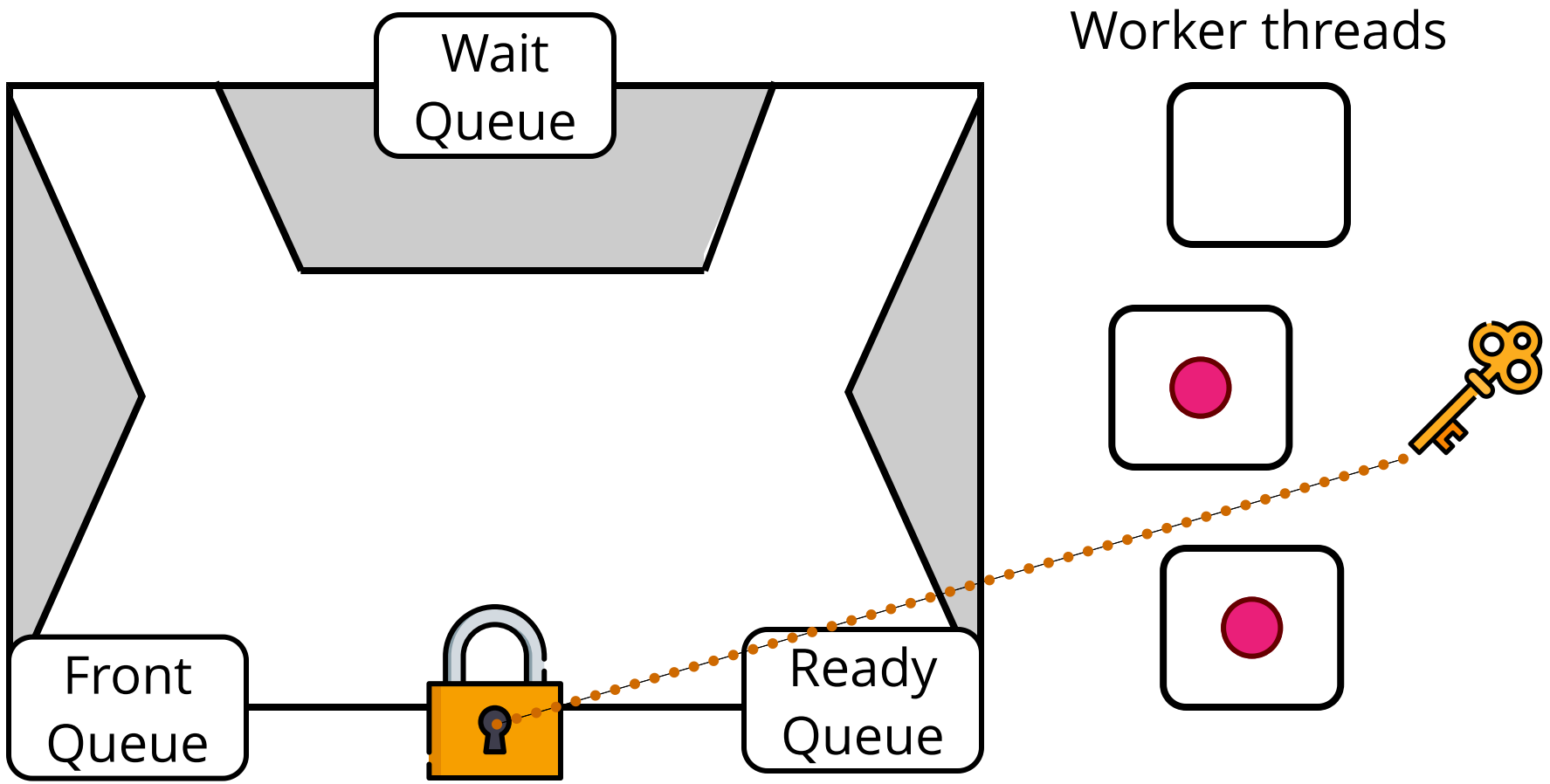
TaskScheduler



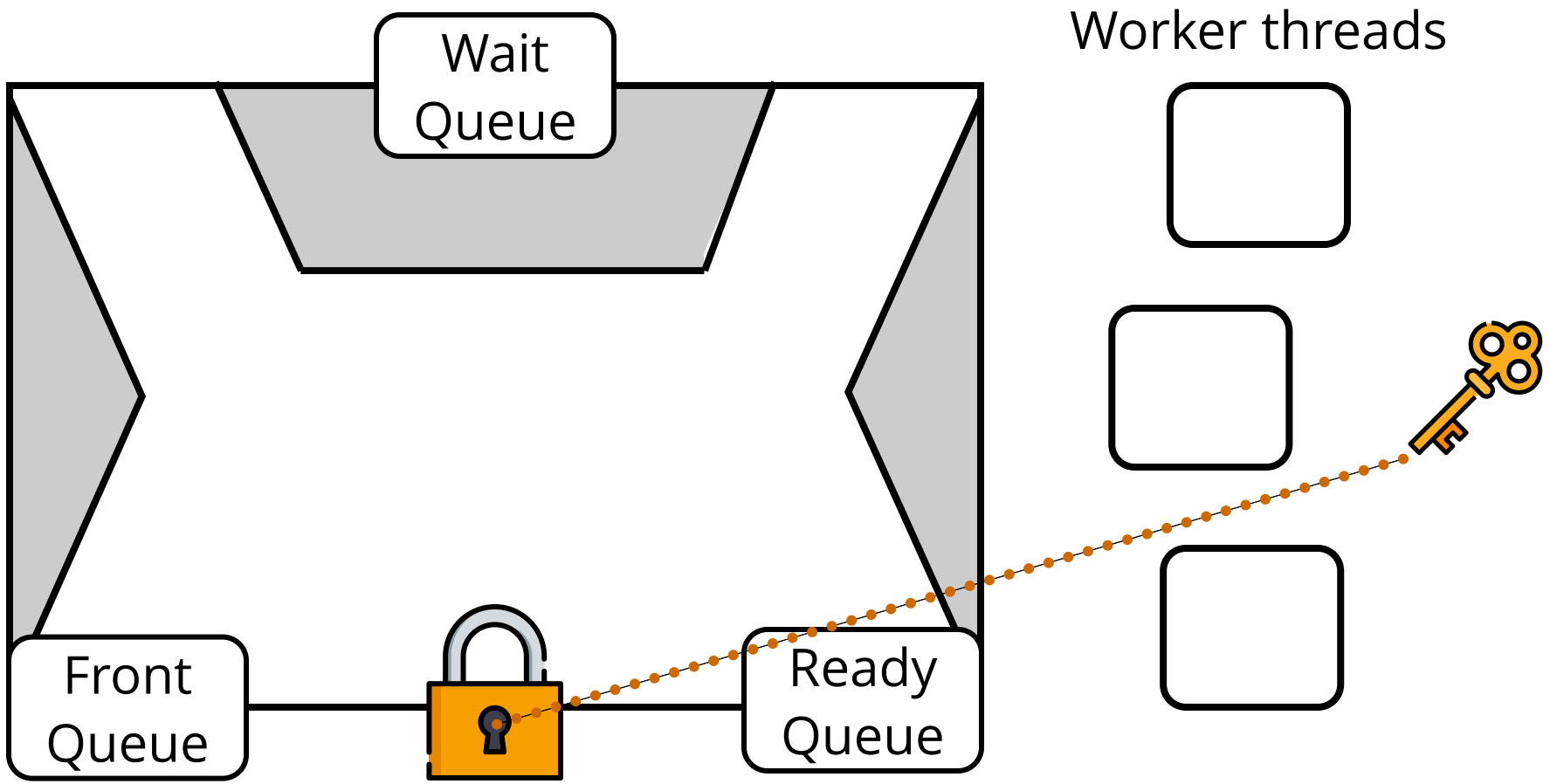
TaskScheduler



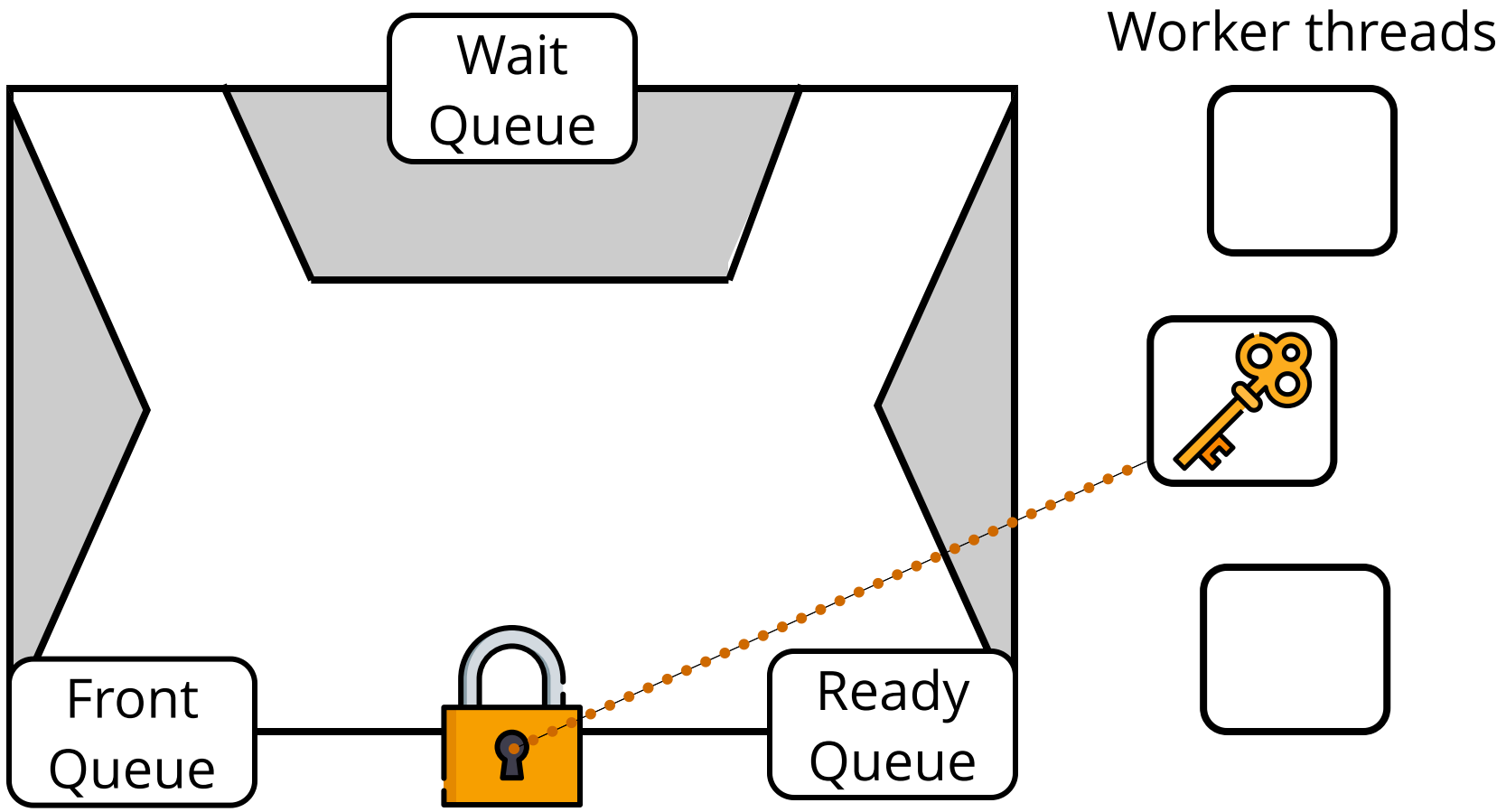
TaskScheduler



TaskScheduler



TaskScheduler



Dependencies

Mutex

Containers

Condition variable

Lock-free atomics

Lock-free atomics

Atomically get the old value

```
AtomicLoad(var)
{
    return var;
}
```

* Google "**memory models**" about why it has to be atomic

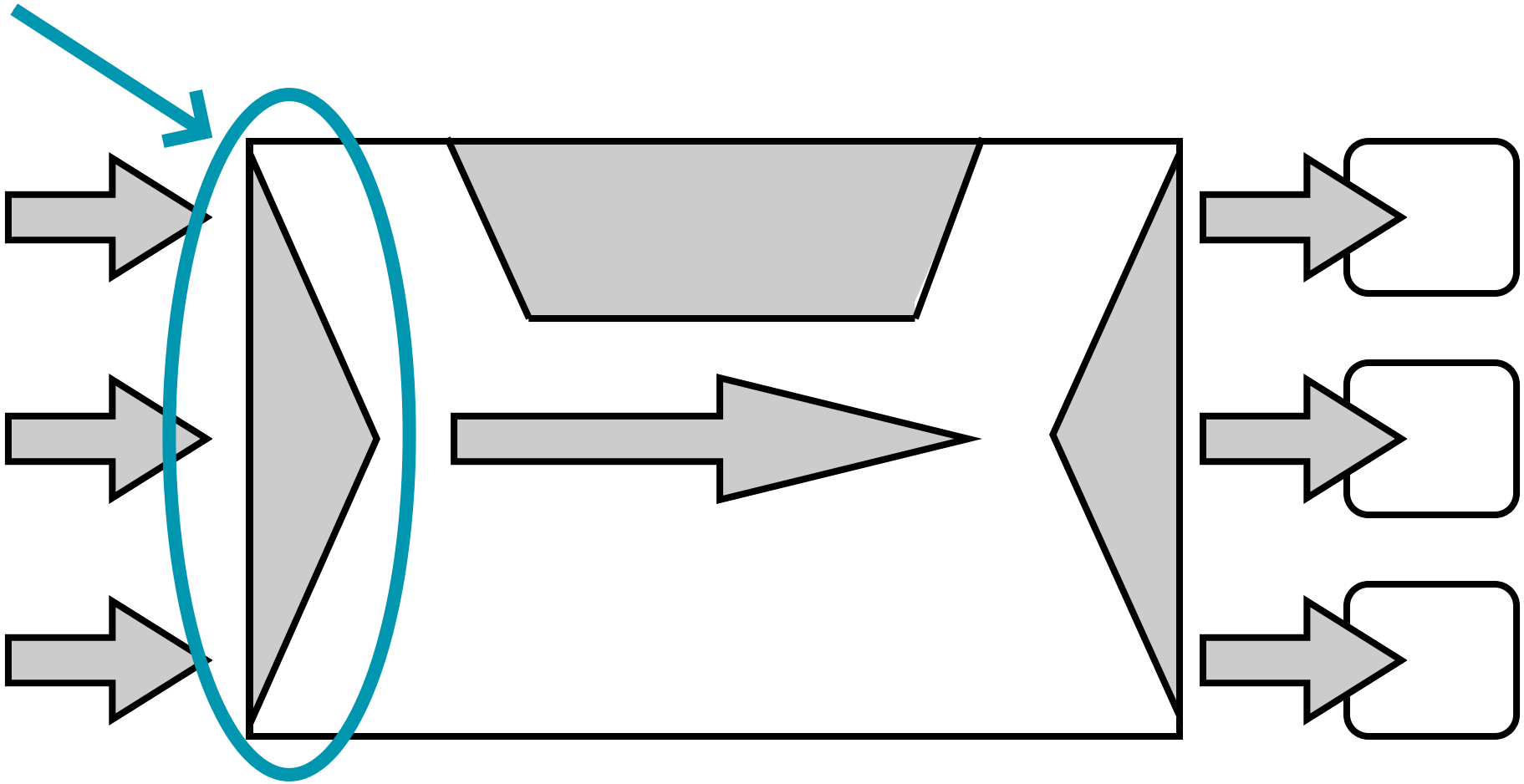
Atomically set if the old value equals something

```
AtomicCompareExchange(var, new_value, check)
{
    if (var != check)
        return false;
    var = new_value;
    return true;
}
```

Atomically set a new value and get the old value

```
AtomicExchange(var, new_value)
{
    old_value = var;
    var = new_value;
    return old_value;
}
```

Front queue

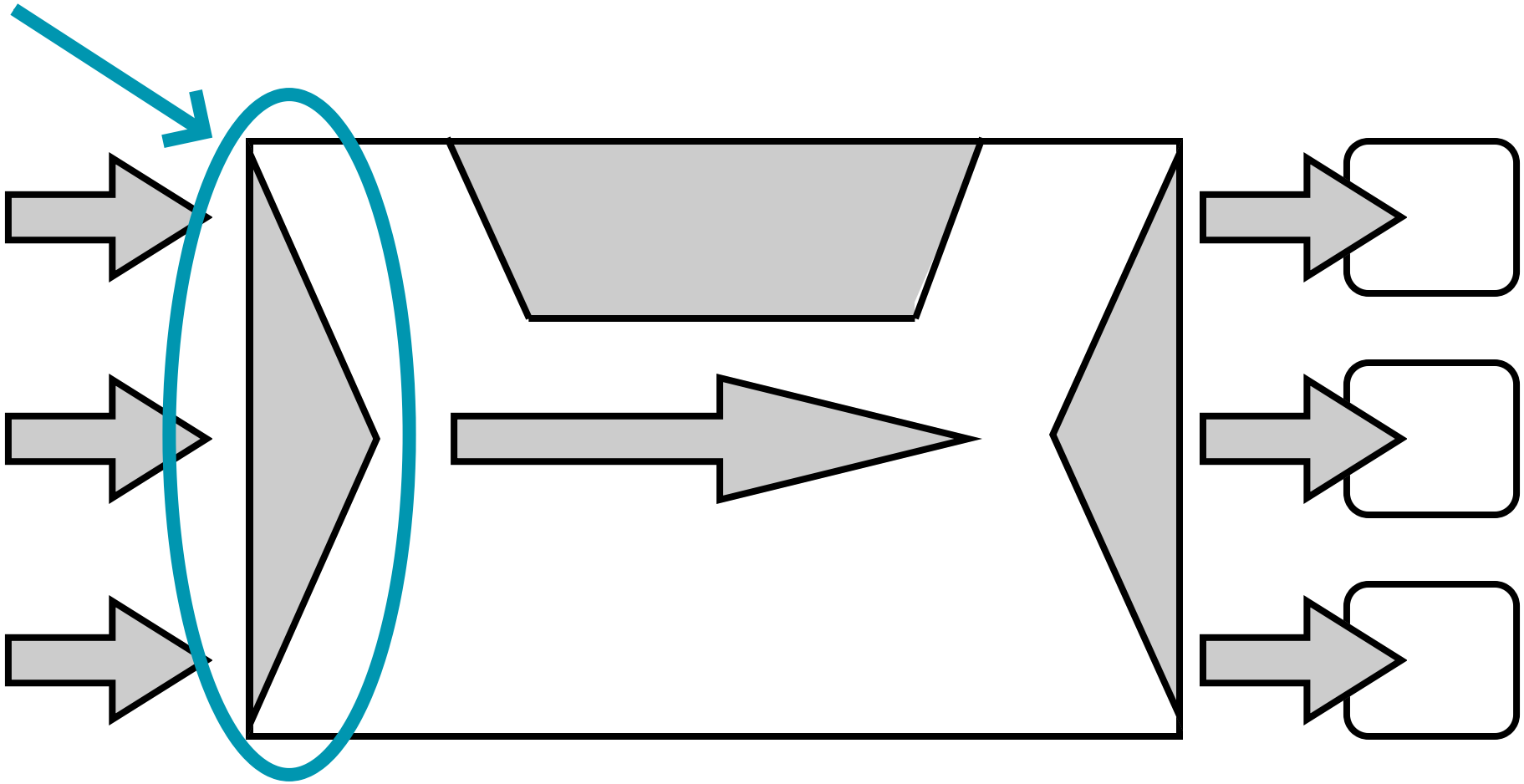


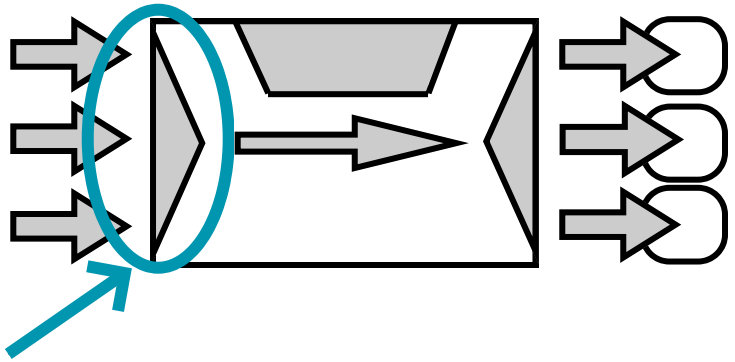
Front queue

Multi-Producer-Single-Consumer*

All threads — Sched-worker

* Common notation for queues:
MPSC, MPMC, SPSC, SPMC



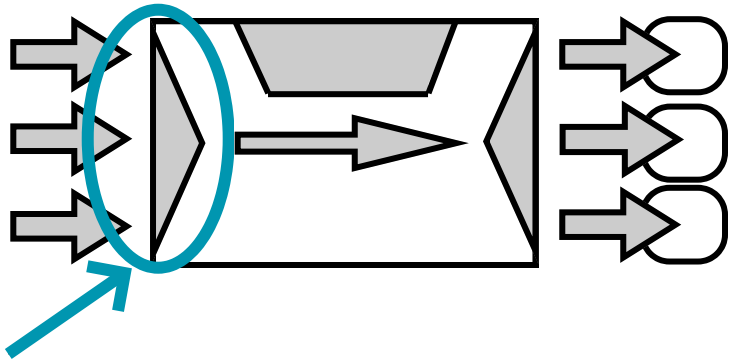


Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

High contention



Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

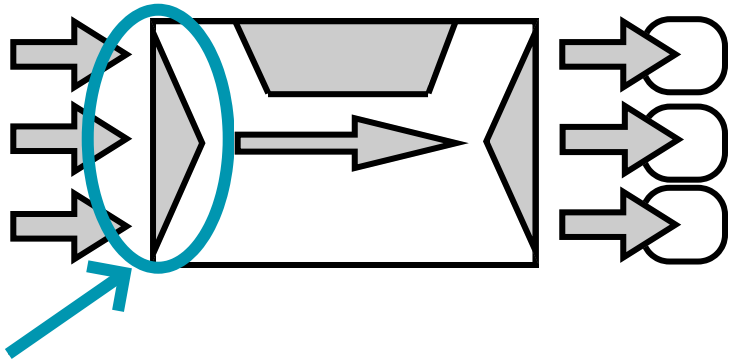
High contention

```
class NormalQueue:
    T* myHead;
    T* myTail;
```

```
NormalQueue::Push(T* aItem)
{
    if (myHead == nullptr)
        myHead = aItem;
    else
        myTail->myNext = aItem;
    myTail = aItem;
}

NormalQueue::Pop()
{
    if (myHead == nullptr)
        return nullptr;
    T* res = myHead;
    myHead = res->myNext;
    return res;
}
```

Normally a queue needs 2 members: **head** and **tail**



Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

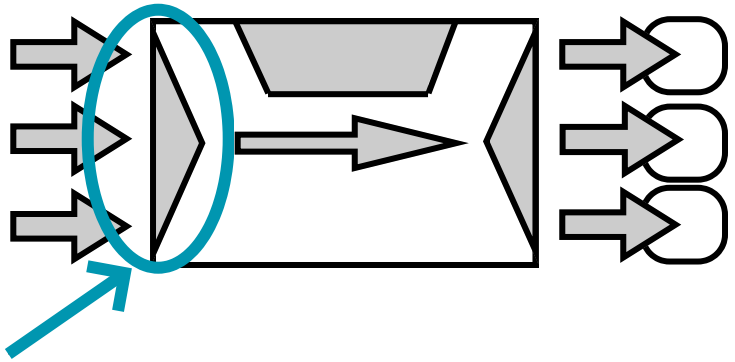
High contention

```
class NormalQueue:
    T* myHead;
    T* myTail;
```

```
NormalQueue::Push(T* aItem)
{
    if (myHead == nullptr)
        myHead = aItem;
    else
        myTail->myNext = aItem;
    myTail = aItem;
}

NormalQueue::Pop()
{
    if (myHead == nullptr)
        return nullptr;
    T* res = myHead;
    myHead = res->myNext;
    return res;
}
```

Doing it in a lock-free way is hardly possible - **too many variables**



Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

High contention

```
class MPSCQueue:
    T* myTop;
```

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    do {
        oldTop = AtomicLoad(myTop);
        aItem->myNext = oldTop;
    } while (not AtomicCompareExchange(
        myTop, aItem, oldTop));
}

MPSCQueue::PopAll(T* aItem)
{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Make it a **stack** to reduce the number of variables

UBISOFT

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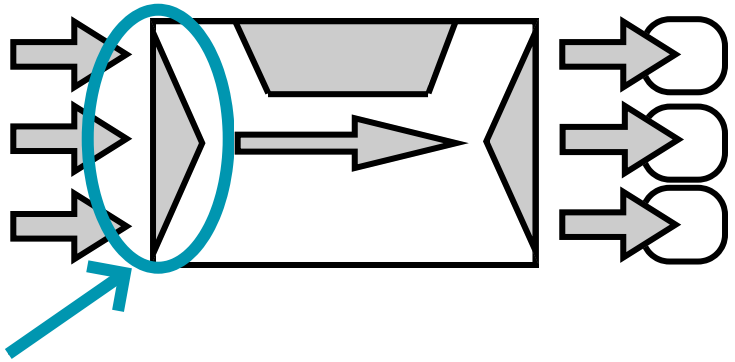


Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

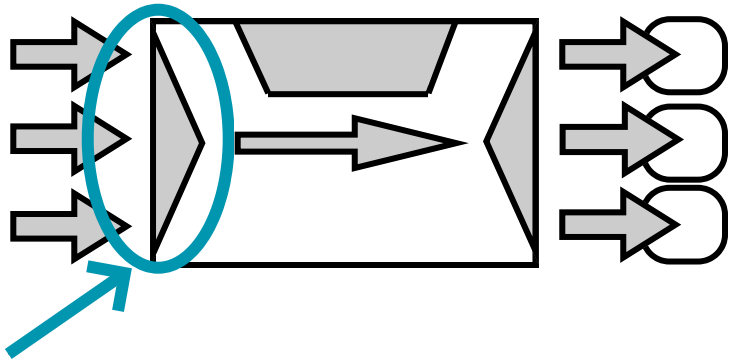
High contention

```
class MPSCQueue:
    T* myTop;
```

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    do {
        oldTop = AtomicLoad(myTop);
        aItem->myNext = oldTop;
    } while (not AtomicCompareExchange(
        myTop, aItem, oldTop));
}

MPSCQueue::PopAll(T* aItem)
{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Retry **atomic push** of a new top. Stack grows



Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

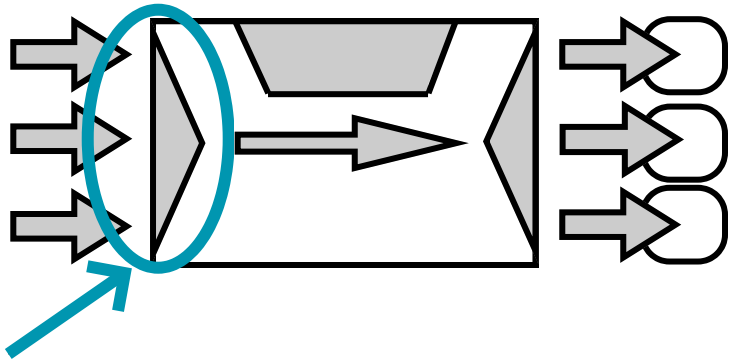
High contention

```
class MPSCQueue:
    T* myTop;
```

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    do {
        oldTop = AtomicLoad(myTop);
        aItem->myNext = oldTop;
    } while (not AtomicCompareExchange(
        myTop, aItem, oldTop));
}

MPSCQueue::PopAll(T* aItem)
{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Pop **takes all** and turns **stack to queue**



Front queue

Multi-Producer-Single-Consumer

All threads | Sched-worker

High contention

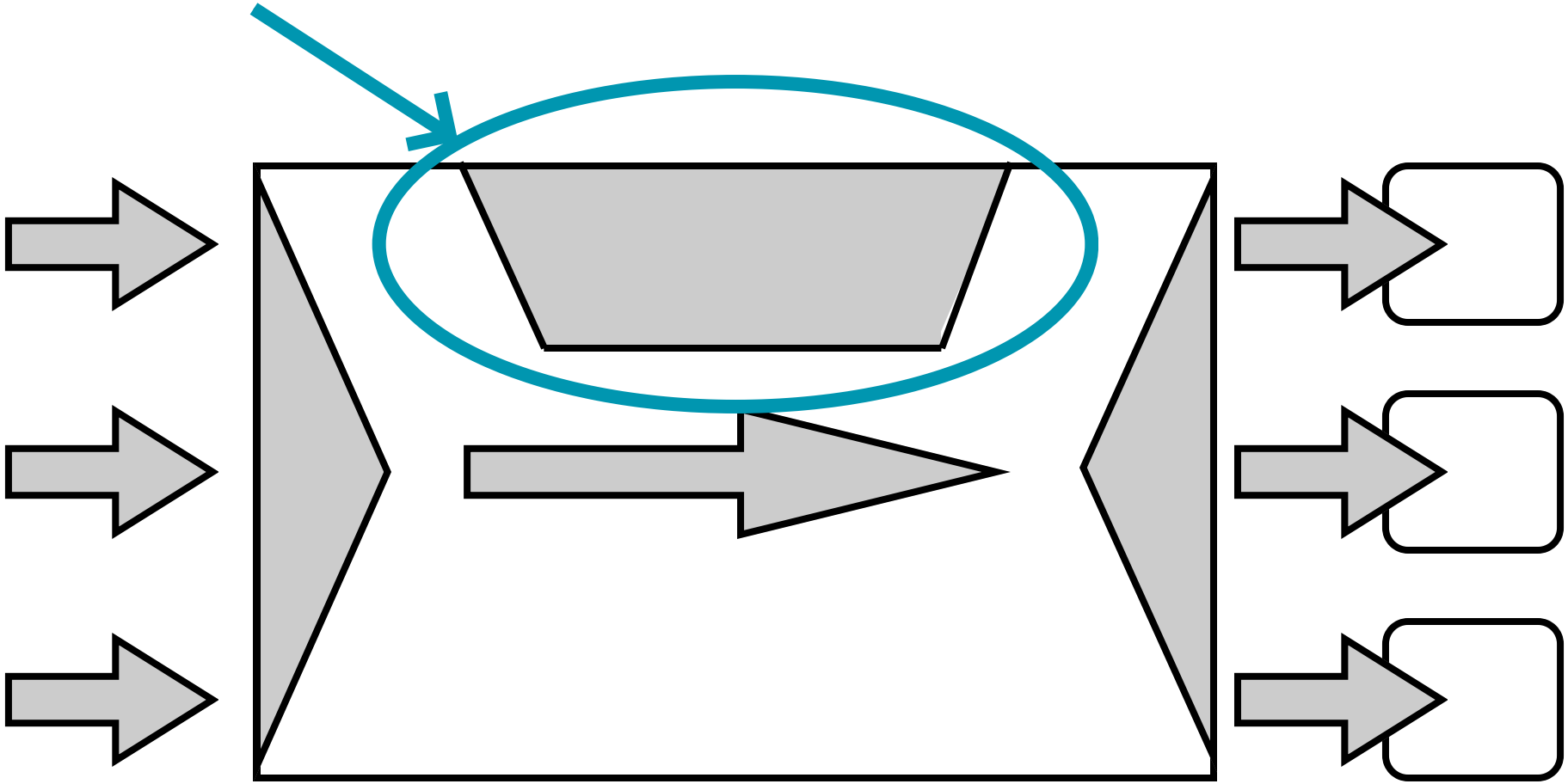
Completely lock-free

```
class MPSCQueue:
    T* myTop;
```

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    do {
        oldTop = AtomicLoad(myTop);
        aItem->myNext = oldTop;
    } while (not AtomicCompareExchange(
        myTop, aItem, oldTop));
}

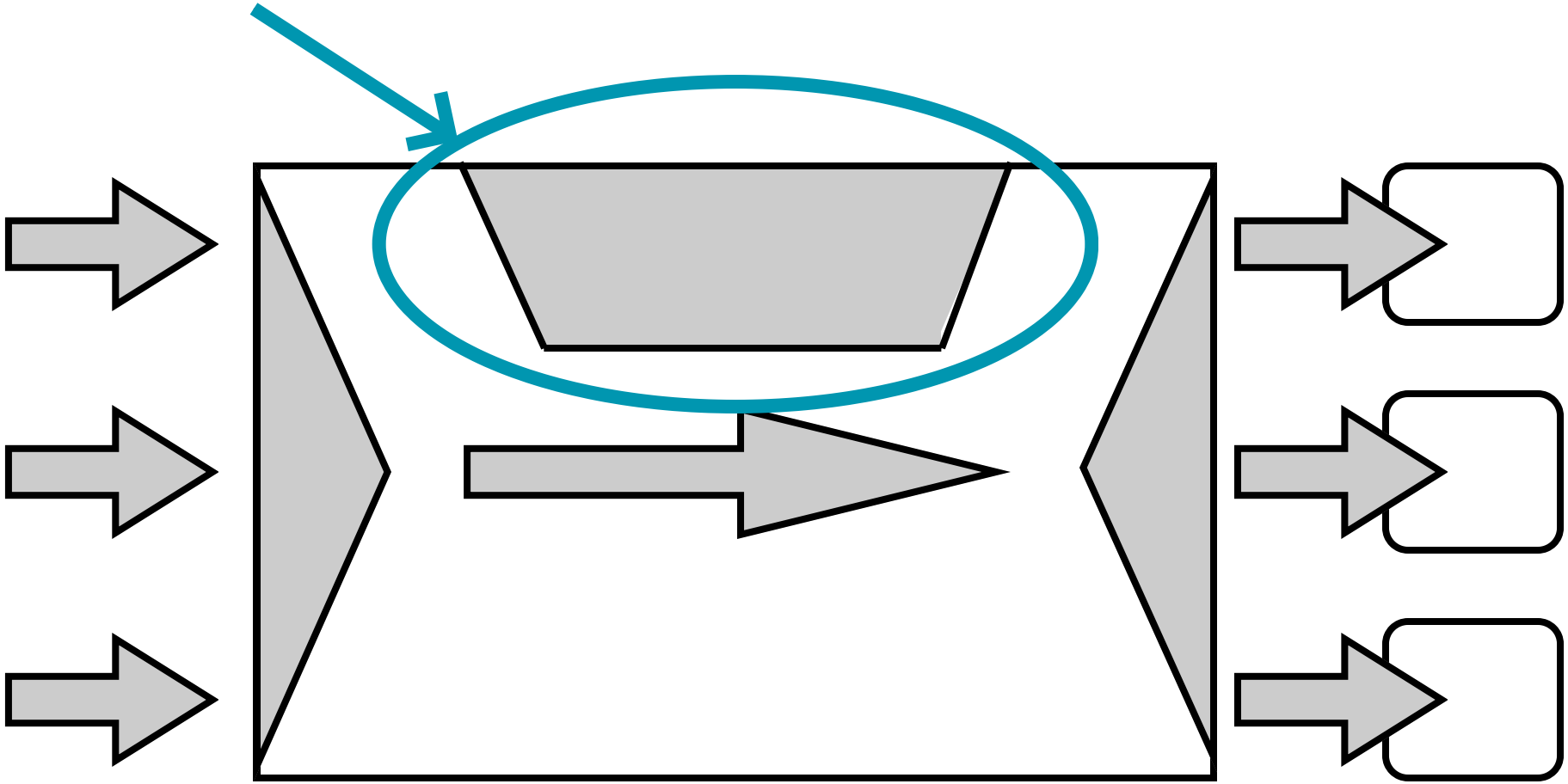
MPSCQueue::PopAll(T* aItem)
{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Wait queue



Wait queue

Quickly get expired tasks

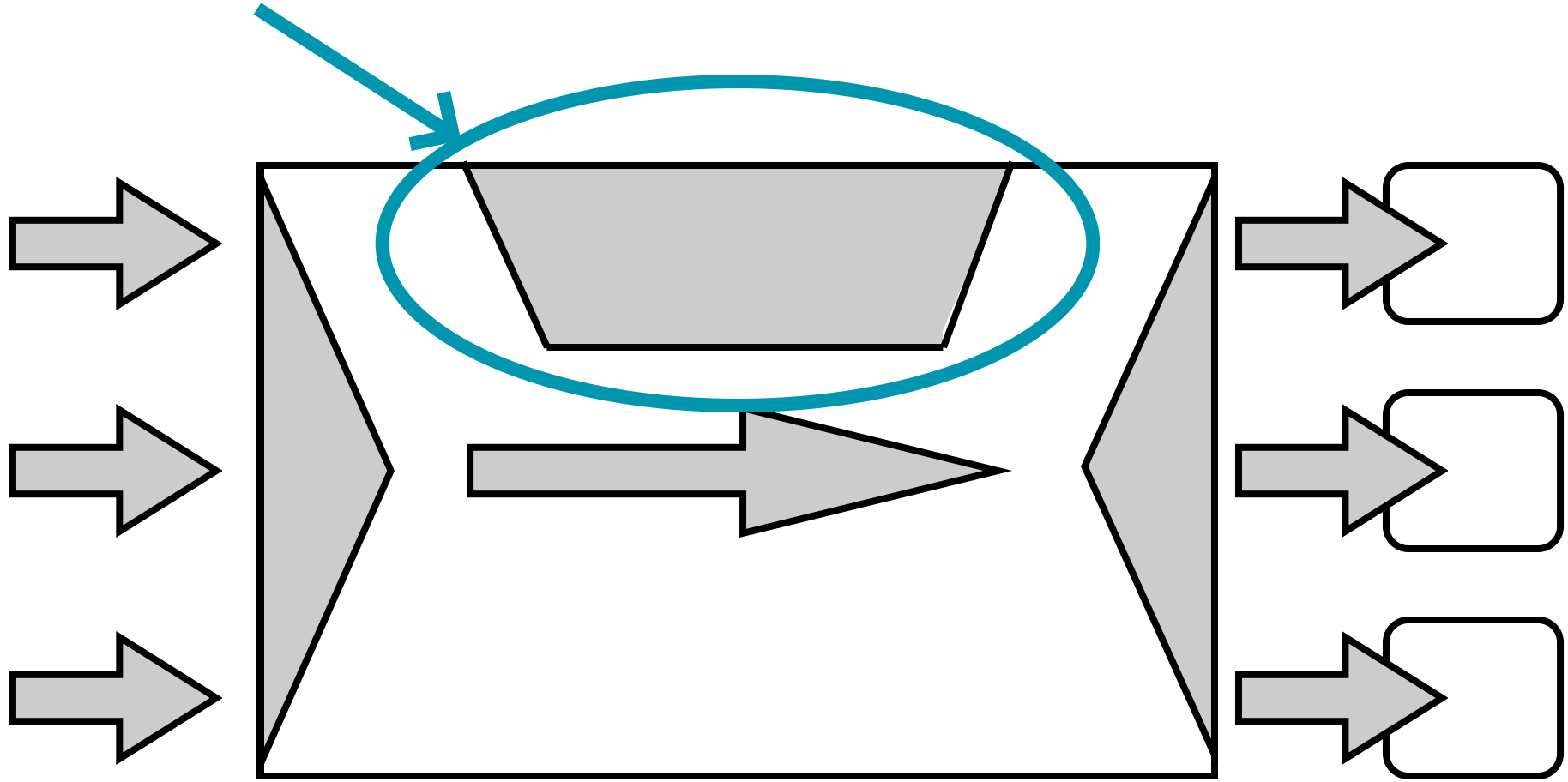


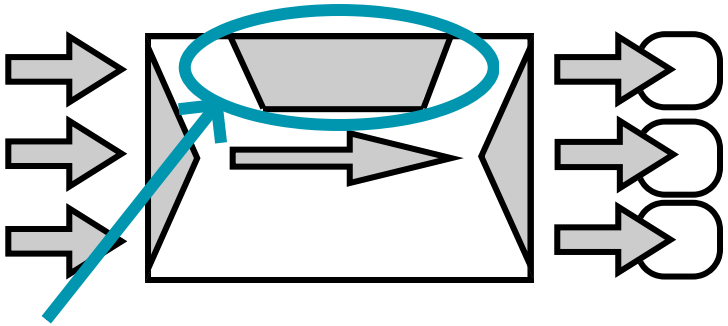
Wait queue

Binary heap

Sched-worker

Quickly get expired tasks





Wait queue

Binary heap

Sched-worker

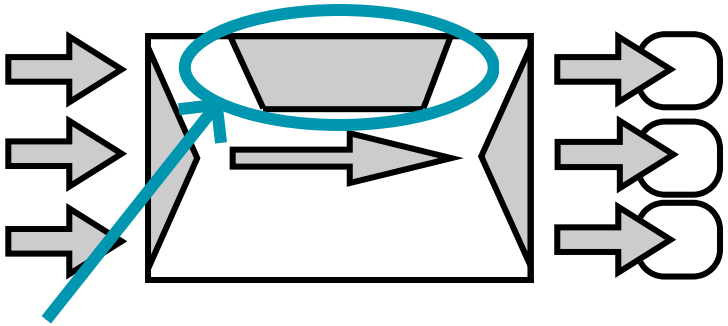
Sort tasks by deadlines - the closest on top

$$O(log(N)) - update$$

$$O(1) - get\ top$$

Quickly get expired tasks

Very good time complexity



Wait queue

Binary heap

Sched-worker

Quickly get expired tasks

Very good time complexity

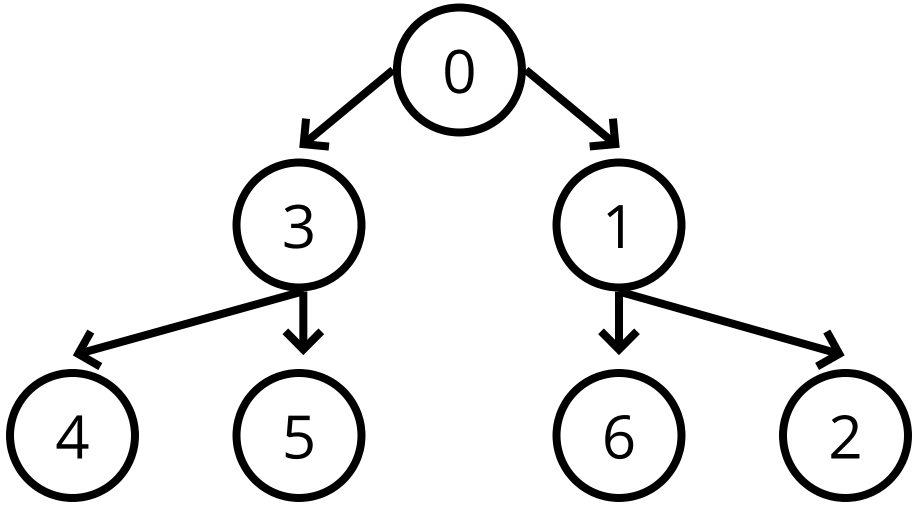
Sort tasks by deadlines - the closest on top

Perfectly balanced binary tree

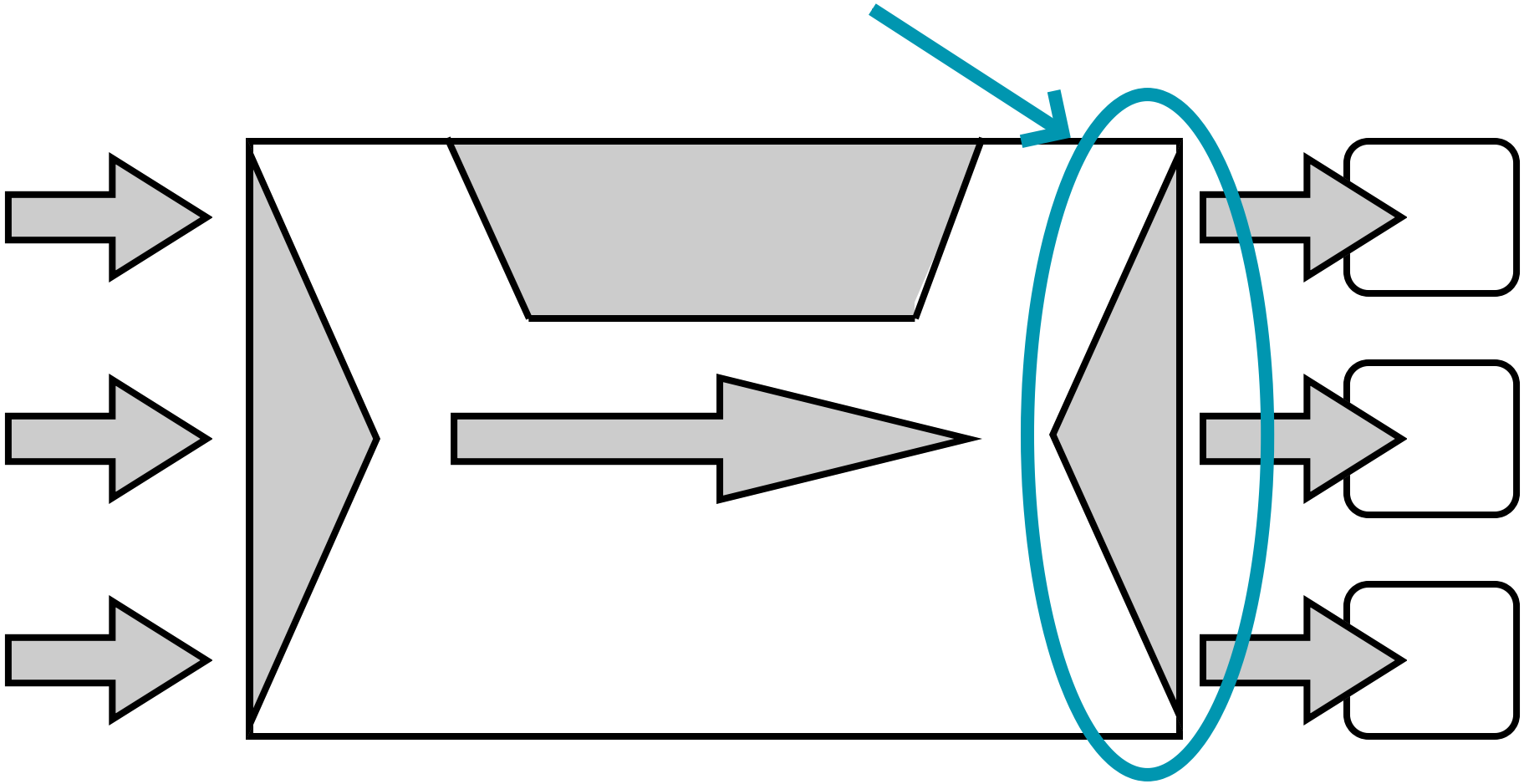
Node <= children

$$O(log(N)) - update$$

$$O(1) - get\ top$$



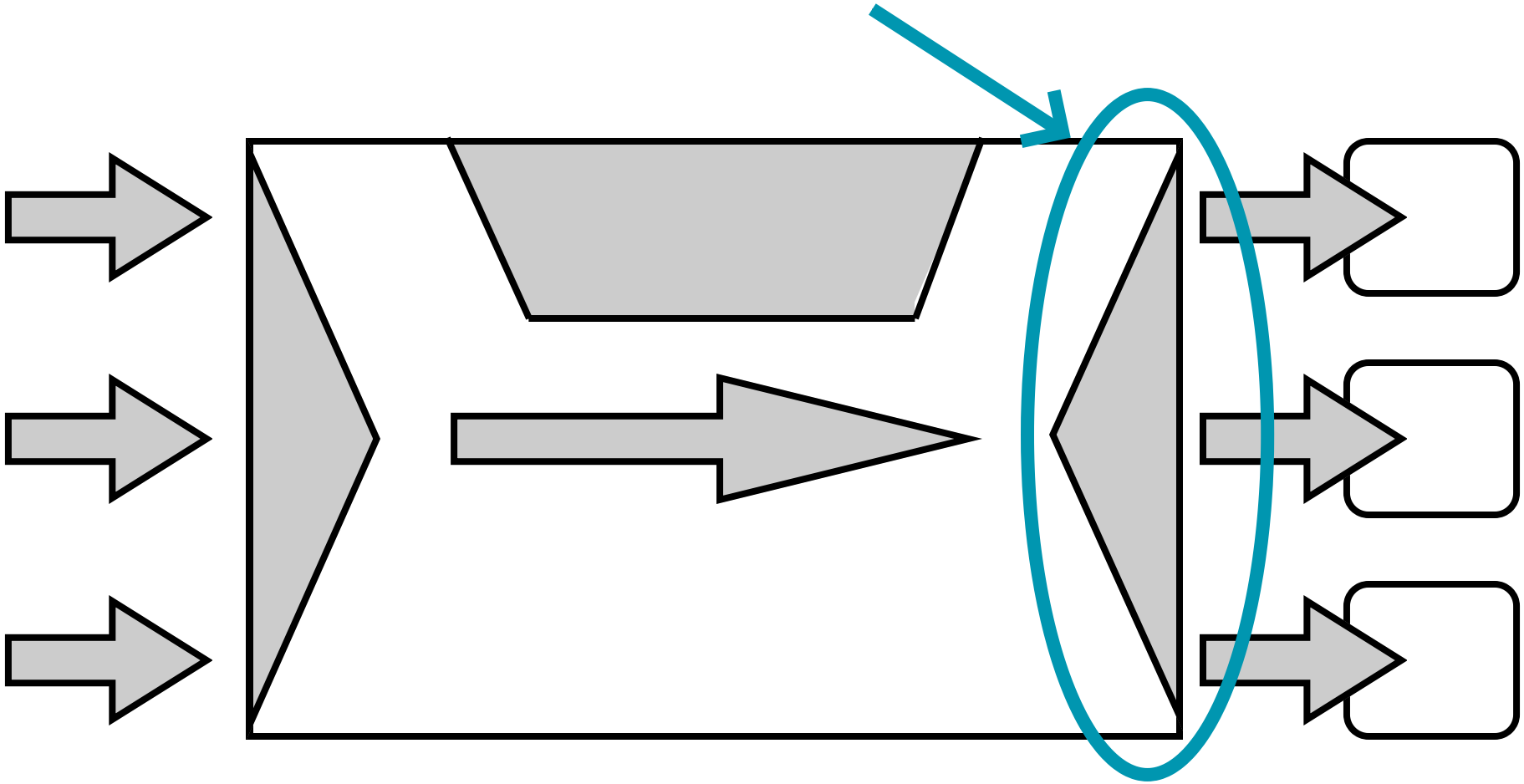
Ready queue



Ready queue

Multi-Consumer-Single-Producer

All threads | Sched-worker

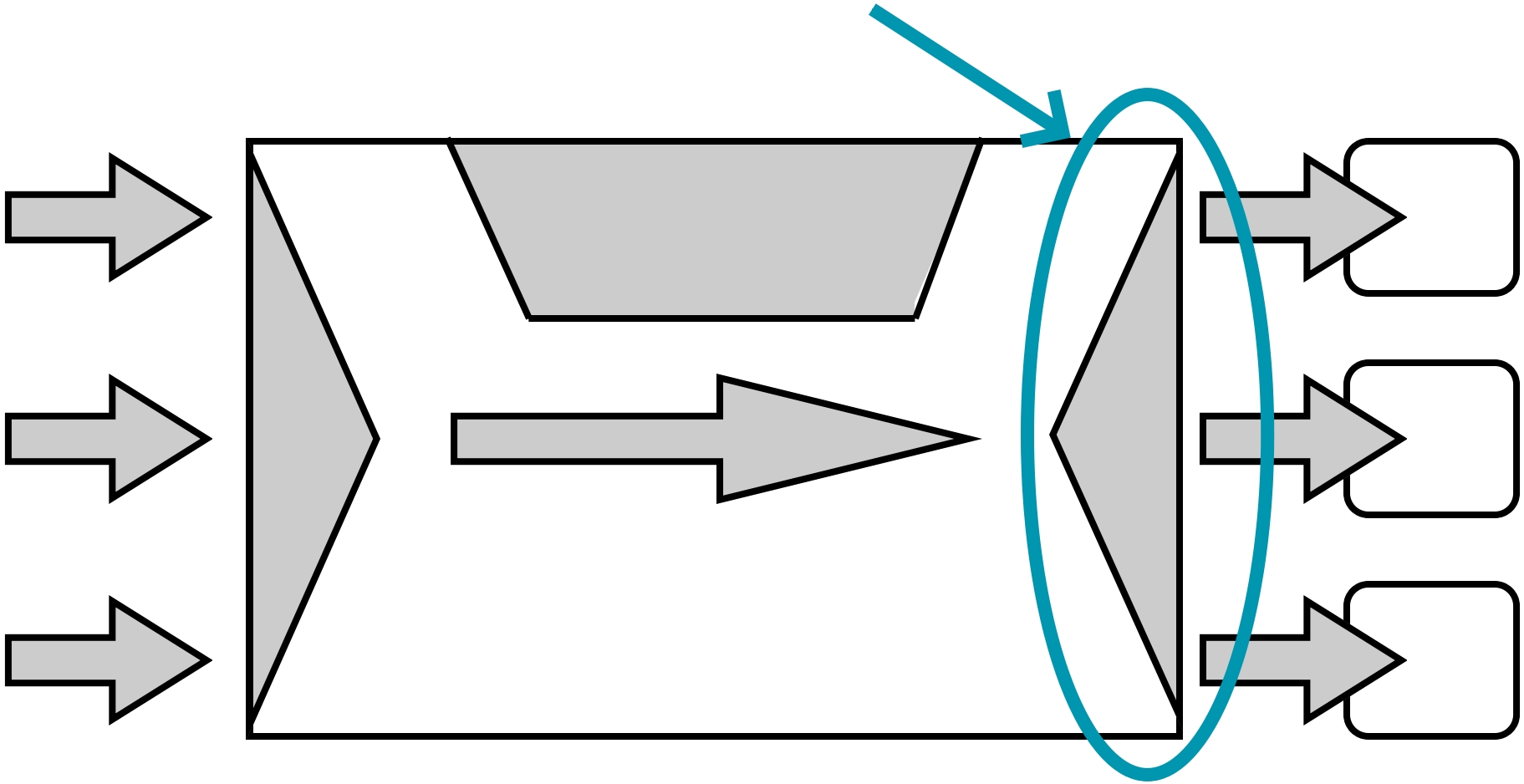


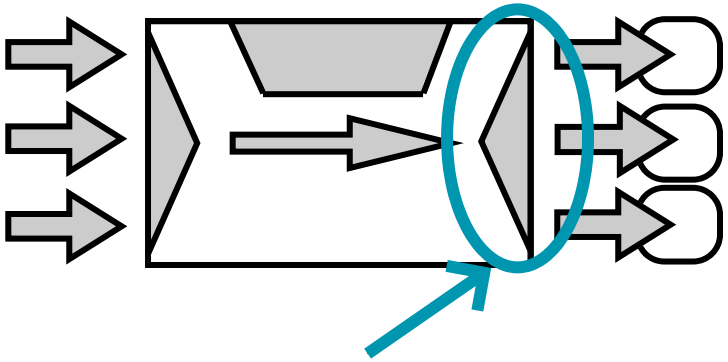
Ready queue

Multi-Consumer-Single-Producer

All threads | Sched-worker

High contention





Ready queue

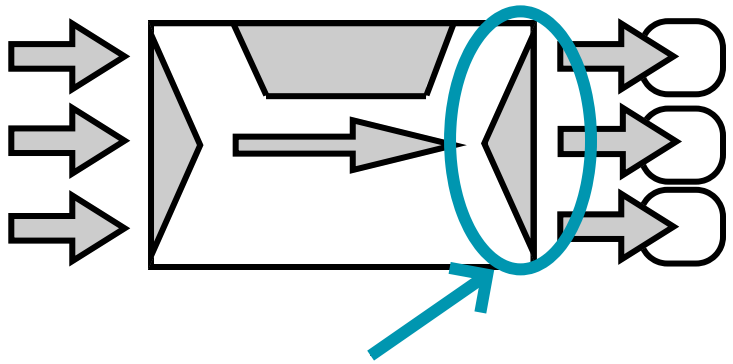
Multi-Consumer-Single-Producer

All threads | Sched-worker

High contention

There is **no** simple unbounded lock-free MCSP queue

* Google "**ABA-problem**" about why



Ready queue

Multi-Consumer-Single-Producer

All threads | Sched-worker

High contention

There is **no** simple unbounded lock-free MCSP queue

* Google "**ABA-problem**" about why

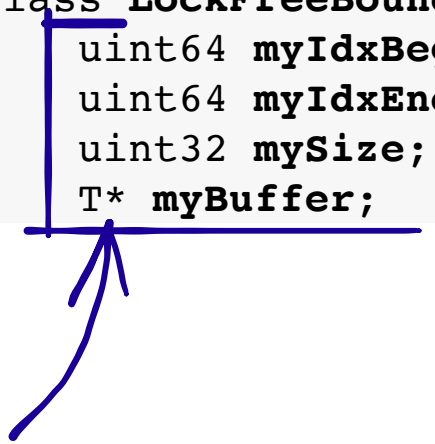
But there **are** these:

Unbounded lock-based MCSP queue

Bounded lock-free MCSP queue

Ready queue - Bounded Lock-Free

```
class LockFreeBounded:
    uint64 myIdxBegin;
    uint64 myIdxEnd;
    uint32 mySize;
    T* myBuffer;
```



Cyclic array with atomic indexes

```
LockFreeBounded::Push(T* aItem)
{
    uint64 idxEnd = AtomicLoad(myIdxEnd);
    if (idxEnd - AtomicLoad(myIdxBegin) == mySize)
        return false;
    myBuffer[idxEnd % mySize] = aItem;
    AtomicExchange(myIdxEnd, idxEnd + 1);
}

LockFreeBounded::Pop()
{
    T* res;
    do {
        uint64 idxBegin = AtomicLoad(myIdxBegin);
        if (idxBegin == AtomicLoad(myIdxEnd))
            return nullptr;
        res = myBuffer[idxBegin % mySize];
    } while (not AtomicCompareExchange(
        myIdxBegin, idxBegin + 1, idxBegin));
    return res;
}
```

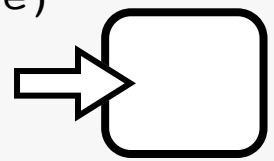
Ready queue - Bounded Lock-Free

```
class LockFreeBounded:
    uint64 myIdxBegin;
    uint64 myIdxEnd;
    uint32 mySize;
    T* myBuffer;
```

Single producer atomically bumps 'end index'

```
LockFreeBounded::Push(T* aItem)
{
    uint64 idxEnd = AtomicLoad(myIdxEnd);
    if (idxEnd - AtomicLoad(myIdxBegin) == mySize)
        return false;
    myBuffer[idxEnd % mySize] = aItem;
    AtomicExchange(myIdxEnd, idxEnd + 1);
}

LockFreeBounded::Pop()
{
    T* res;
    do {
        uint64 idxBegin = AtomicLoad(myIdxBegin);
        if (idxBegin == AtomicLoad(myIdxEnd))
            return nullptr;
        res = myBuffer[idxBegin % mySize];
    } while (not AtomicCompareExchange(
        myIdxBegin, idxBegin + 1, idxBegin));
    return res;
}
```



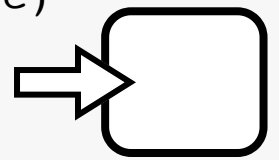
Ready queue - Bounded Lock-Free

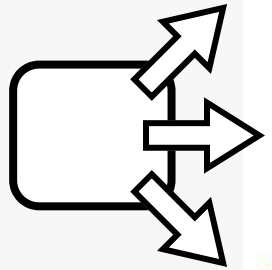
```
class LockFreeBounded:
    uint64 myIdxBegin;
    uint64 myIdxEnd;
    uint32 mySize;
    T* myBuffer;
```

Consumers read by atomically incremented 'begin index'

```
LockFreeBounded::Push(T* aItem)
{
    uint64 idxEnd = AtomicLoad(myIdxEnd);
    if (idxEnd - AtomicLoad(myIdxBegin) == mySize)
        return false;
    myBuffer[idxEnd % mySize] = aItem;
    AtomicExchange(myIdxEnd, idxEnd + 1);
}

LockFreeBounded::Pop()
{
    T* res;
    do {
        uint64 idxBegin = AtomicLoad(myIdxBegin);
        if (idxBegin == AtomicLoad(myIdxEnd))
            return nullptr;
        res = myBuffer[idxBegin % mySize];
    } while (not AtomicCompareExchange(
        myIdxBegin, idxBegin + 1, idxBegin));
    return res;
}
```





Ready queue - Unbounded Locked

```
class LockedUnbounded:
    Mutex myLock;
    List<T> myQueue;
```

Trivial mutex and list

```
LockedUnbounded::Push(T* aItem)
{
    myLock.Lock();
    myQueue.Append(aItem);
    myLock.Unlock();
}

LockedUnbounded::Pop()
{
    myLock.Lock();
    T* res = nullptr;
    if (myQueue.IsEmpty())
        res = myQueue.PopFirst();
    myLock.Unlock();
    return res;
}
```

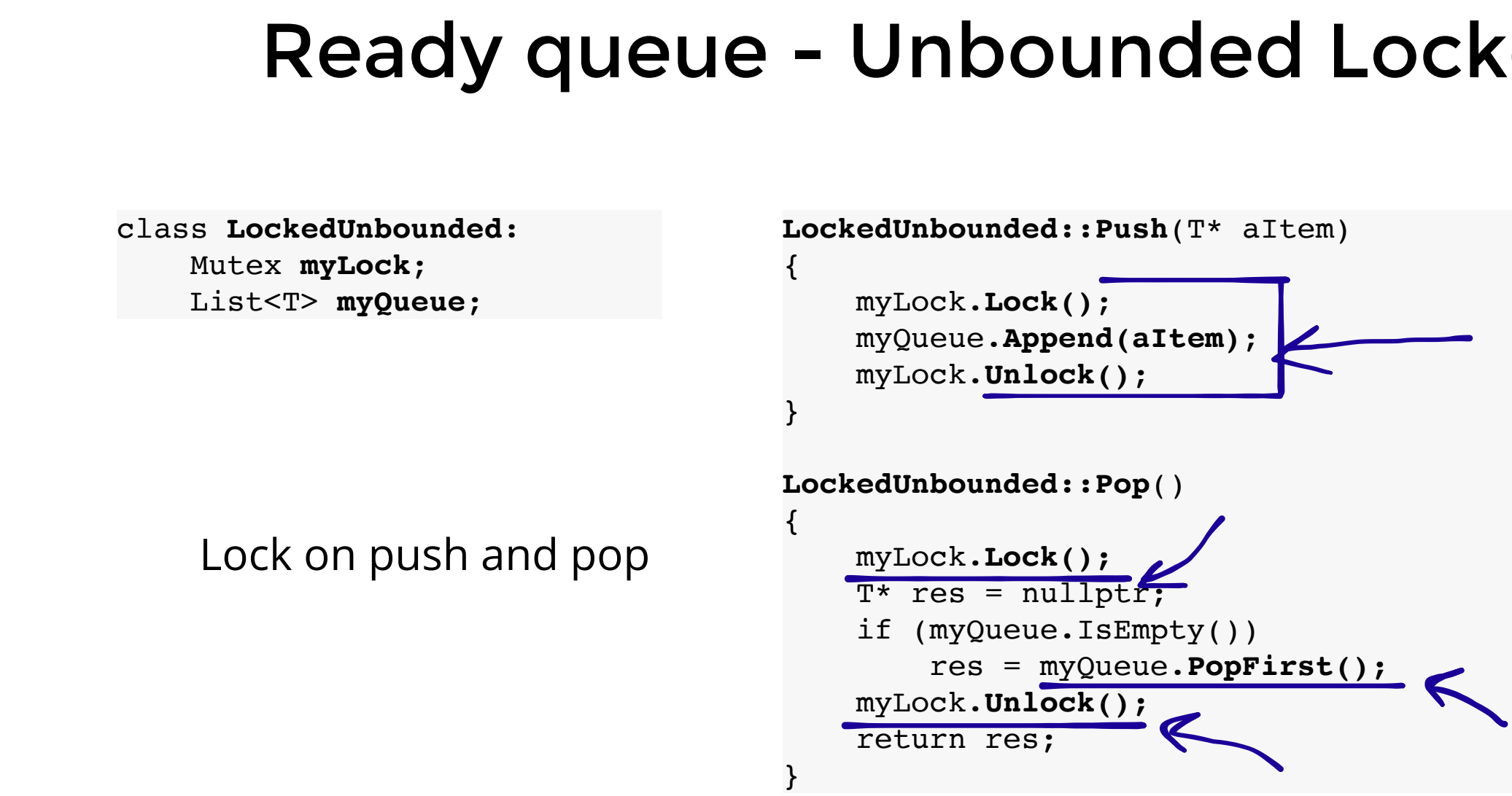
Ready queue - Unbounded Locked

```
class LockedUnbounded:
    Mutex myLock;
    List<T> myQueue;
```

Lock on push and pop

```
LockedUnbounded::Push(T* aItem)
{
    myLock.Lock();
    myQueue.Append(aItem);
    myLock.Unlock();
}

LockedUnbounded::Pop()
{
    myLock.Lock();
    T* res = nullptr;
    if (myQueue.IsEmpty())
        res = myQueue.PopFirst();
    myLock.Unlock();
    return res;
}
```

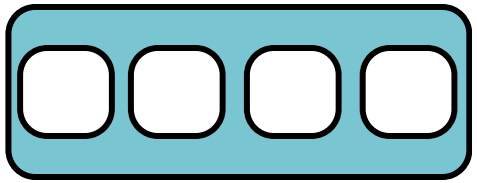


Ready queue

Ready queue

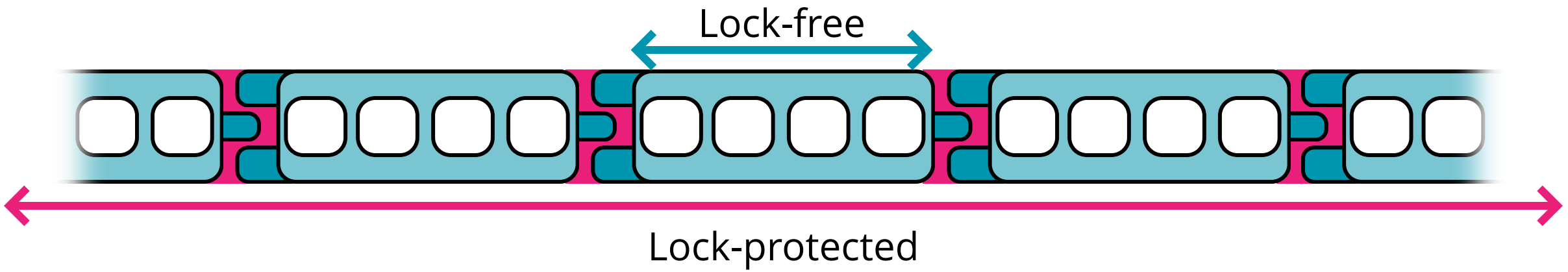
Ready queue

Lock-free



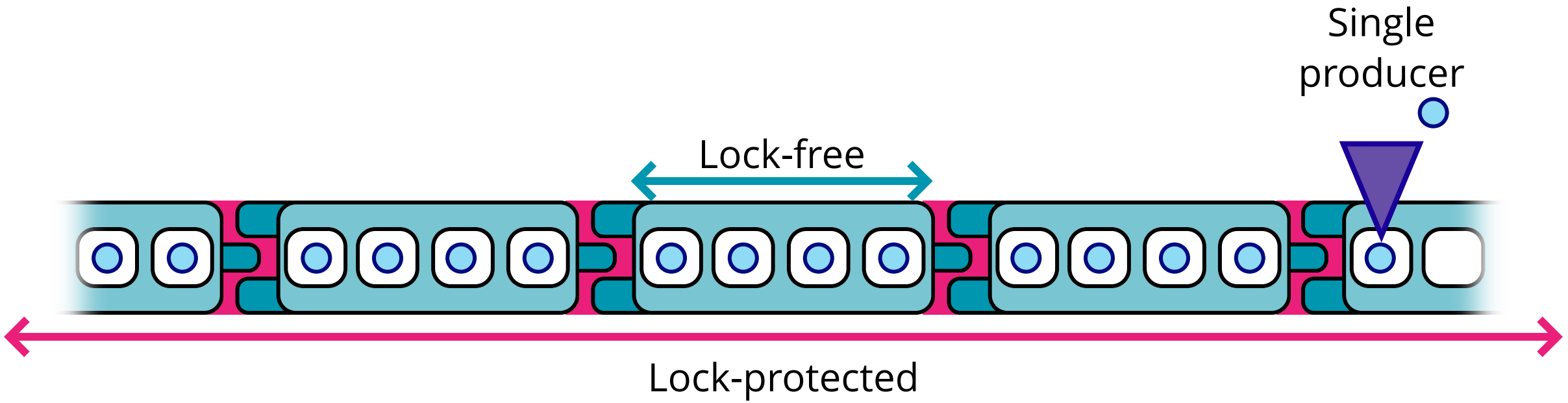
Ready queue

Lock-based **queue of** lock-free **queues**



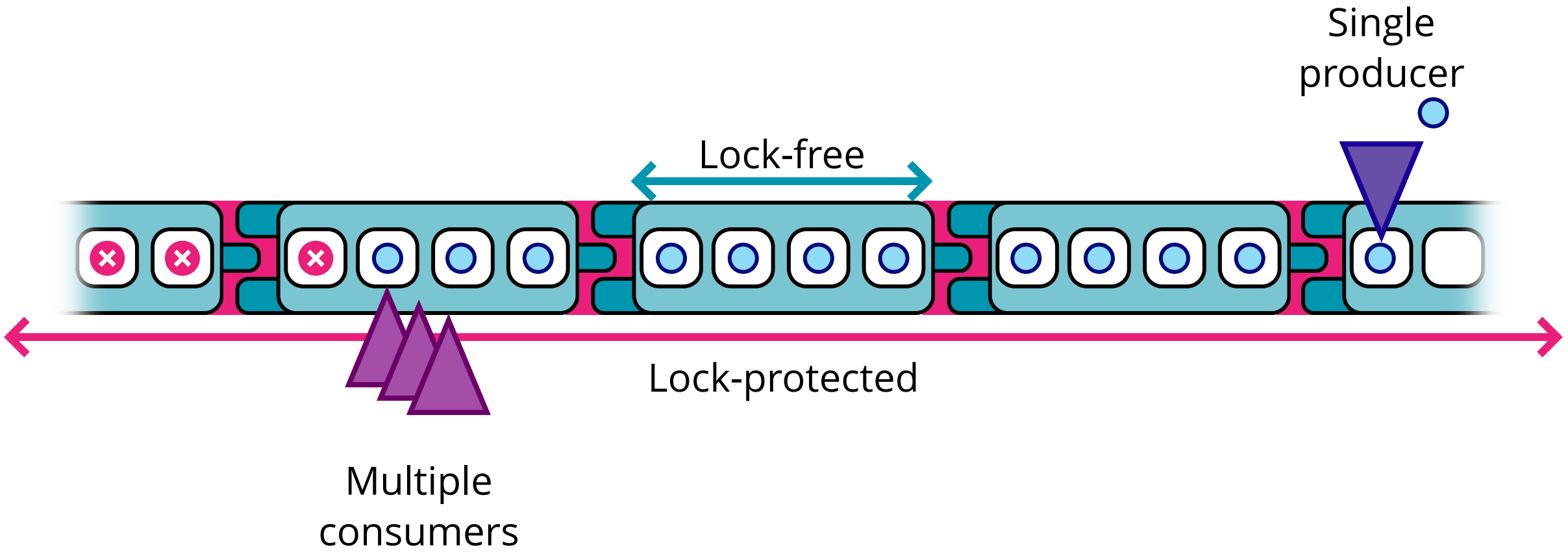
Ready queue

Lock-based **queue of** lock-free **queues**



Ready queue

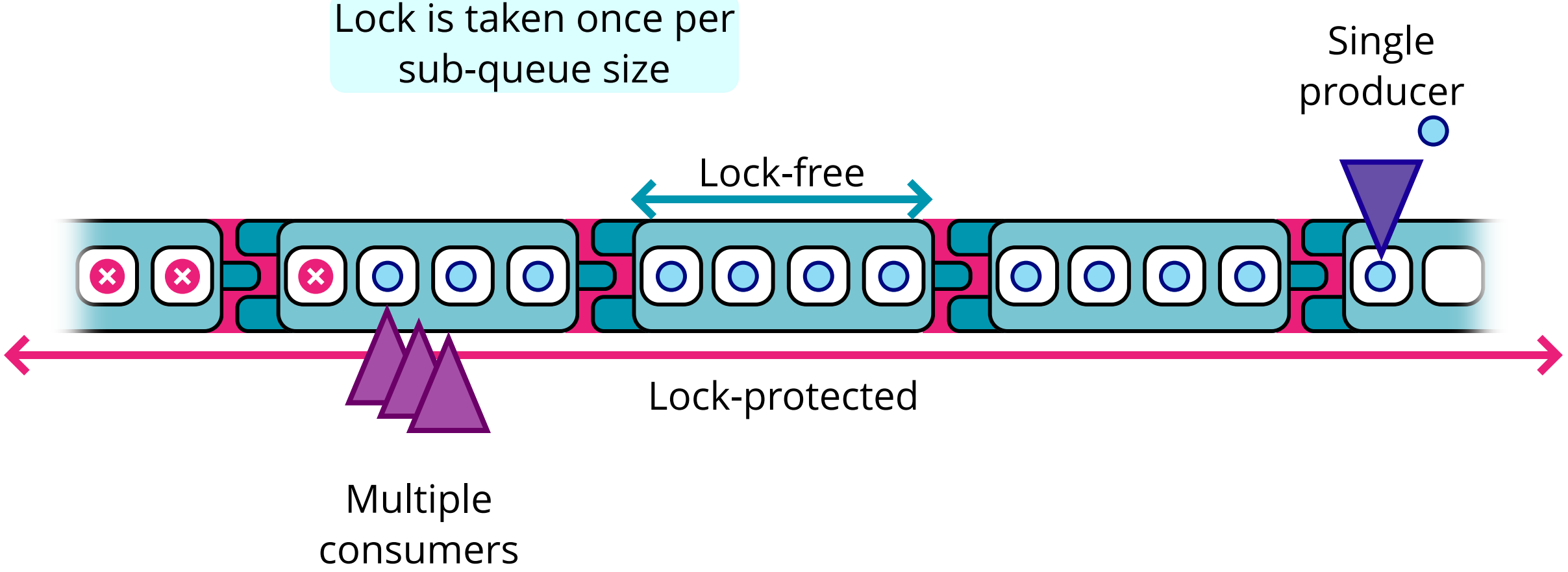
Lock-based **queue of** lock-free **queues**



Ready queue

Lock-based **queue of** lock-free **queues**

Lock is taken once per sub-queue size

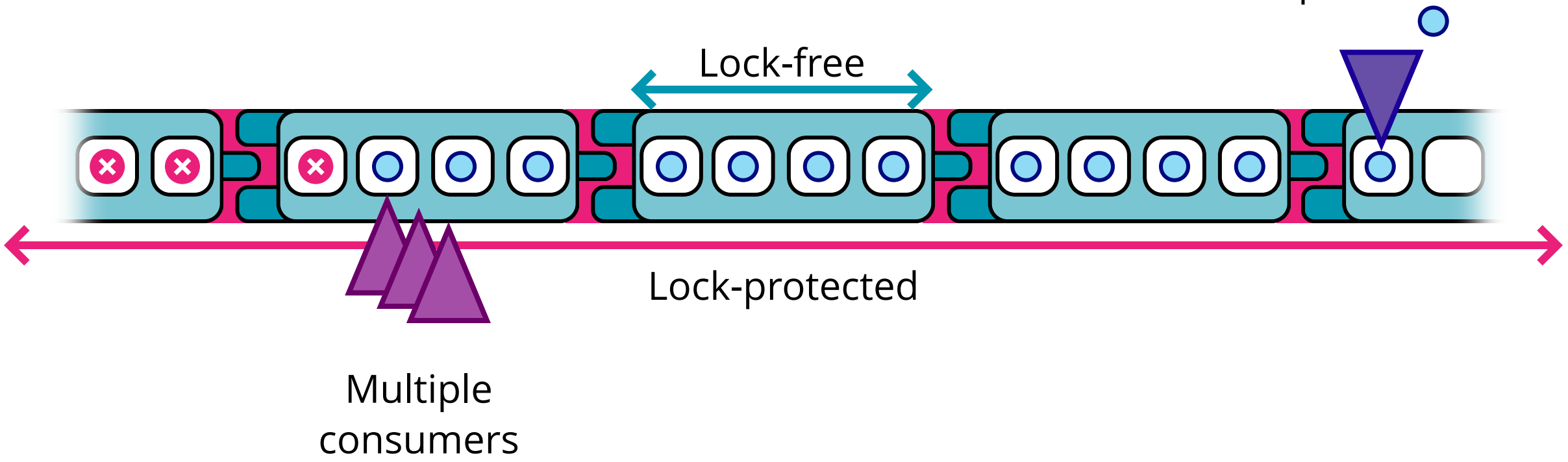


Ready queue

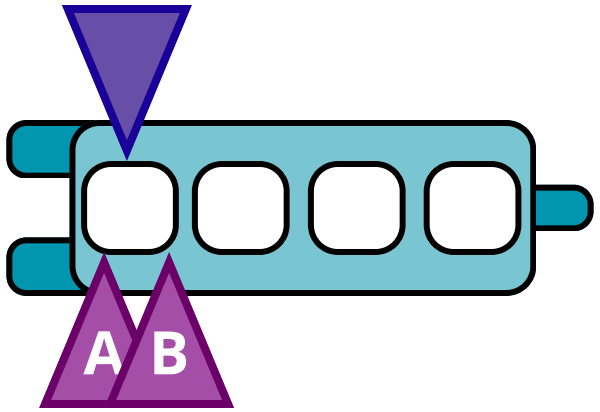
Lock-based **queue of** lock-free **queues**

Lock is taken once per sub-queue size

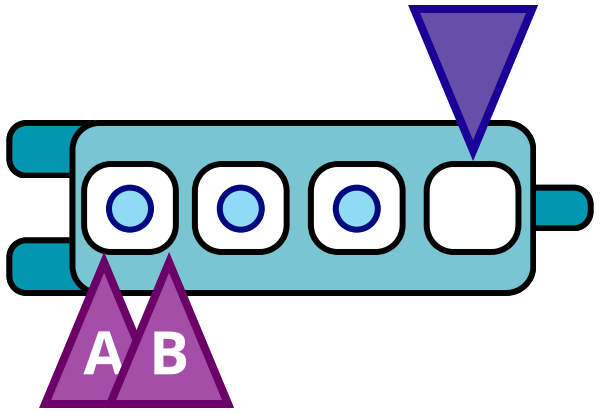
Consumers need an explicit state



Ready queue example



Ready queue example



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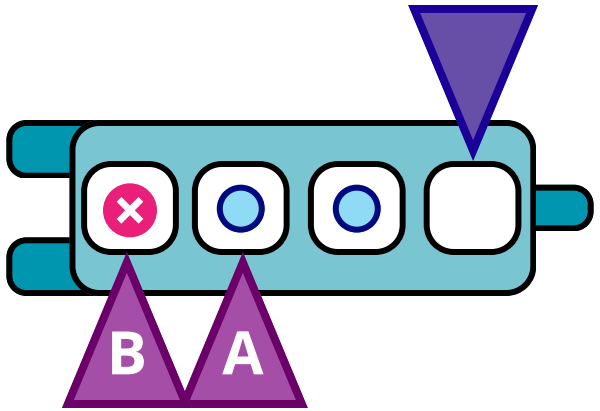
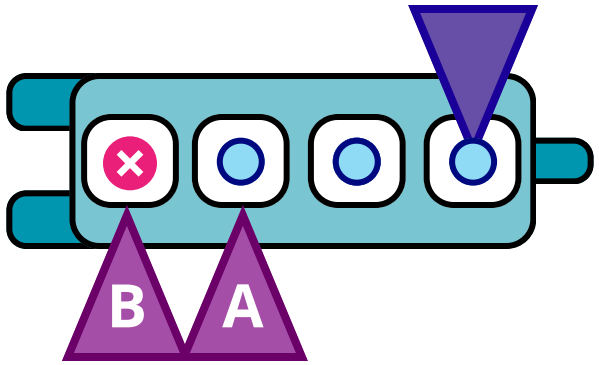


Ready queue example



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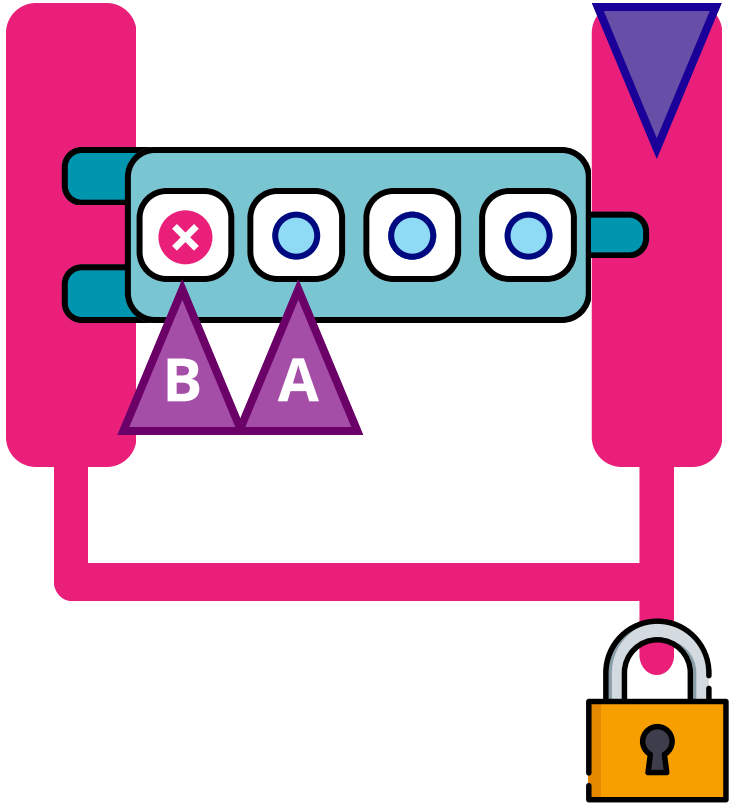
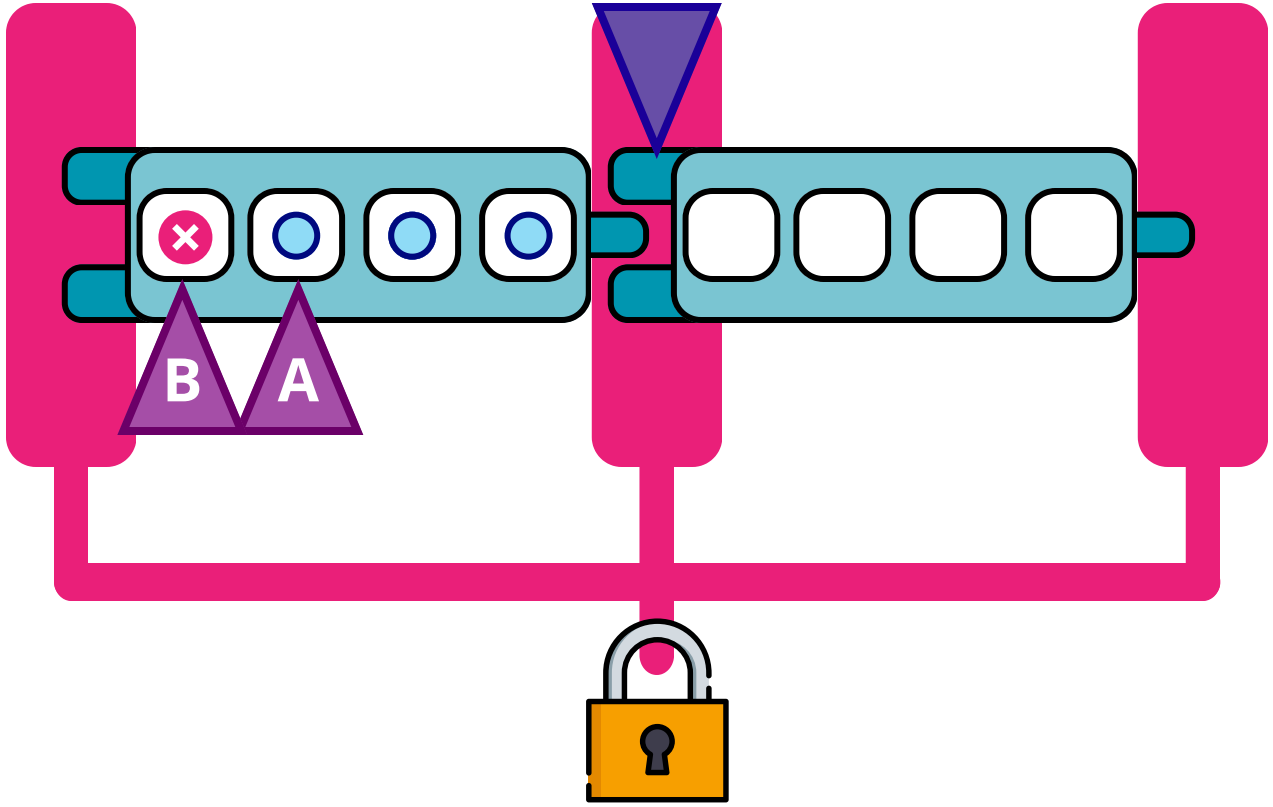


Ready queue example



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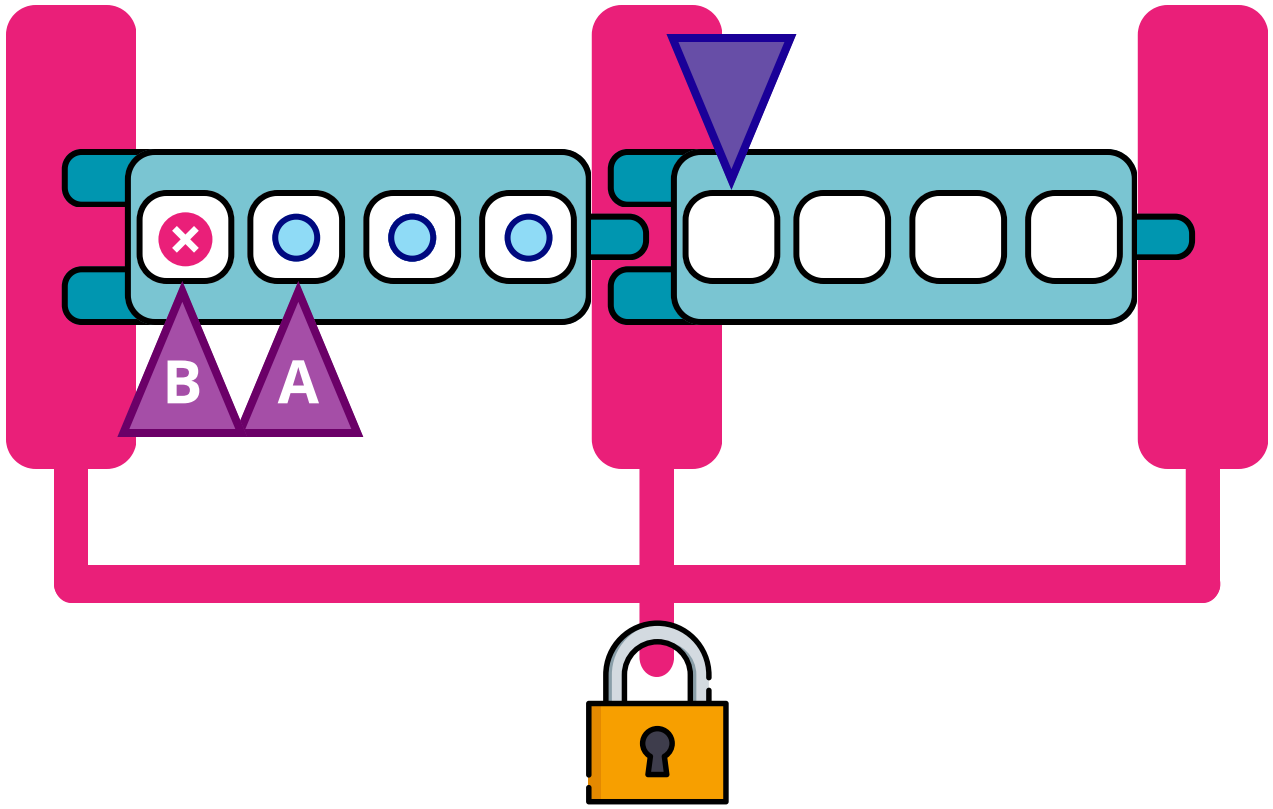

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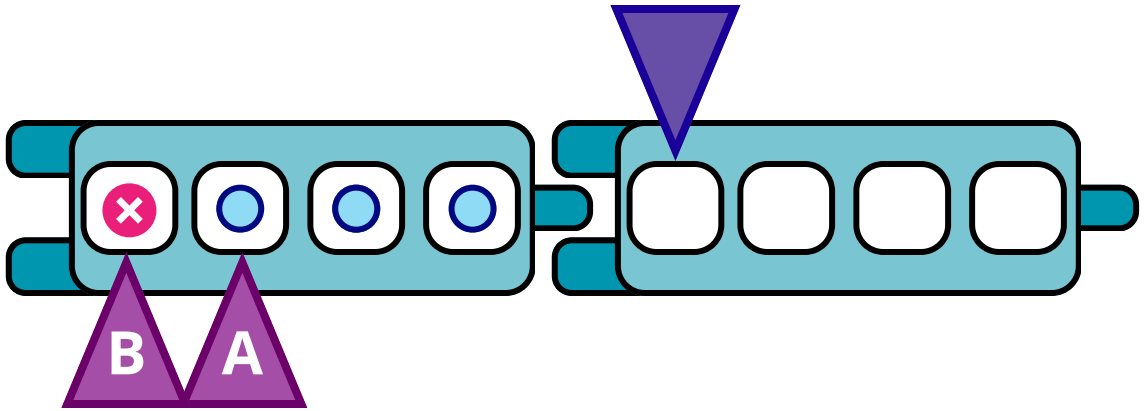

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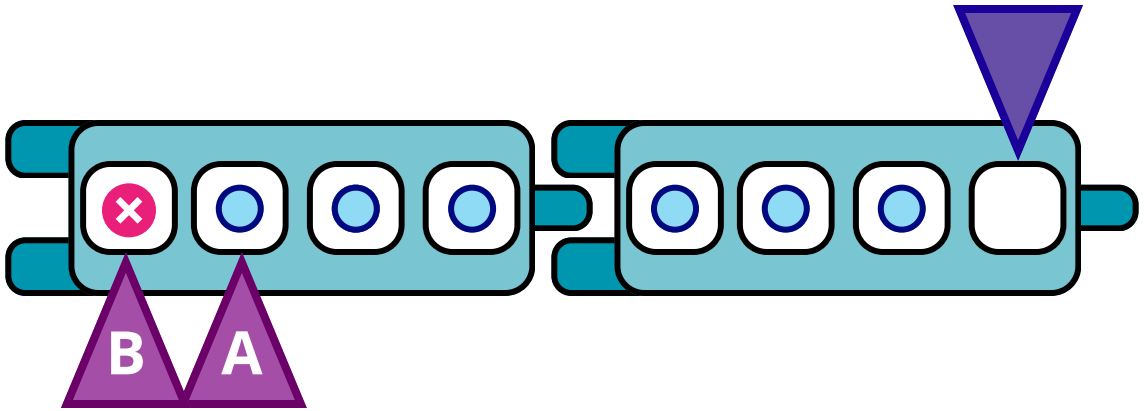
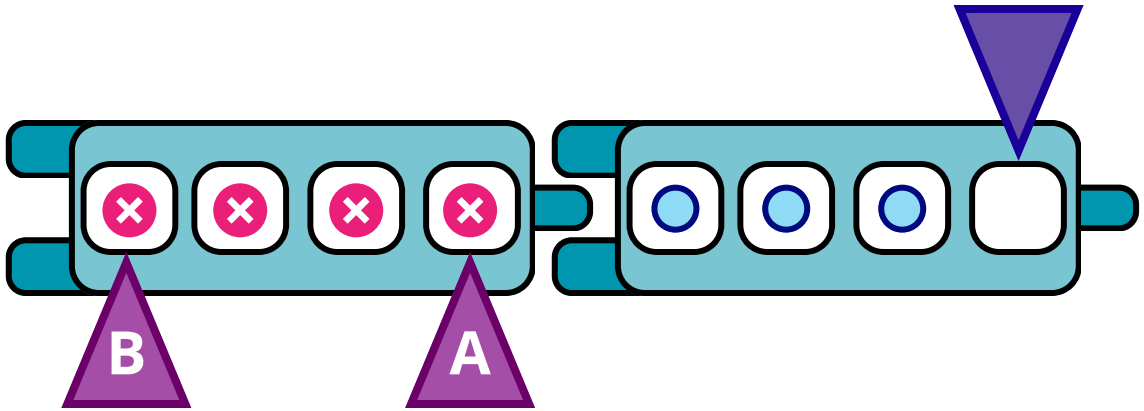
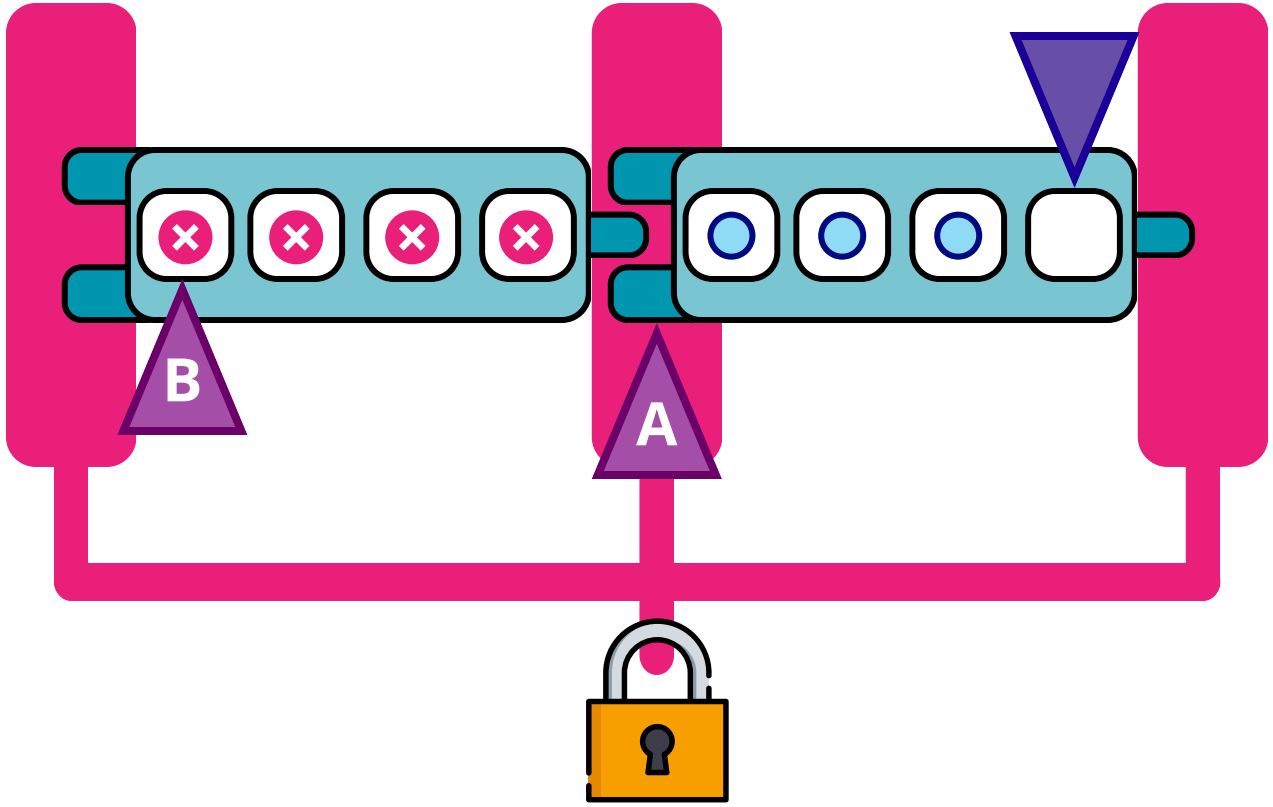


Ready queue example



Ready queue example



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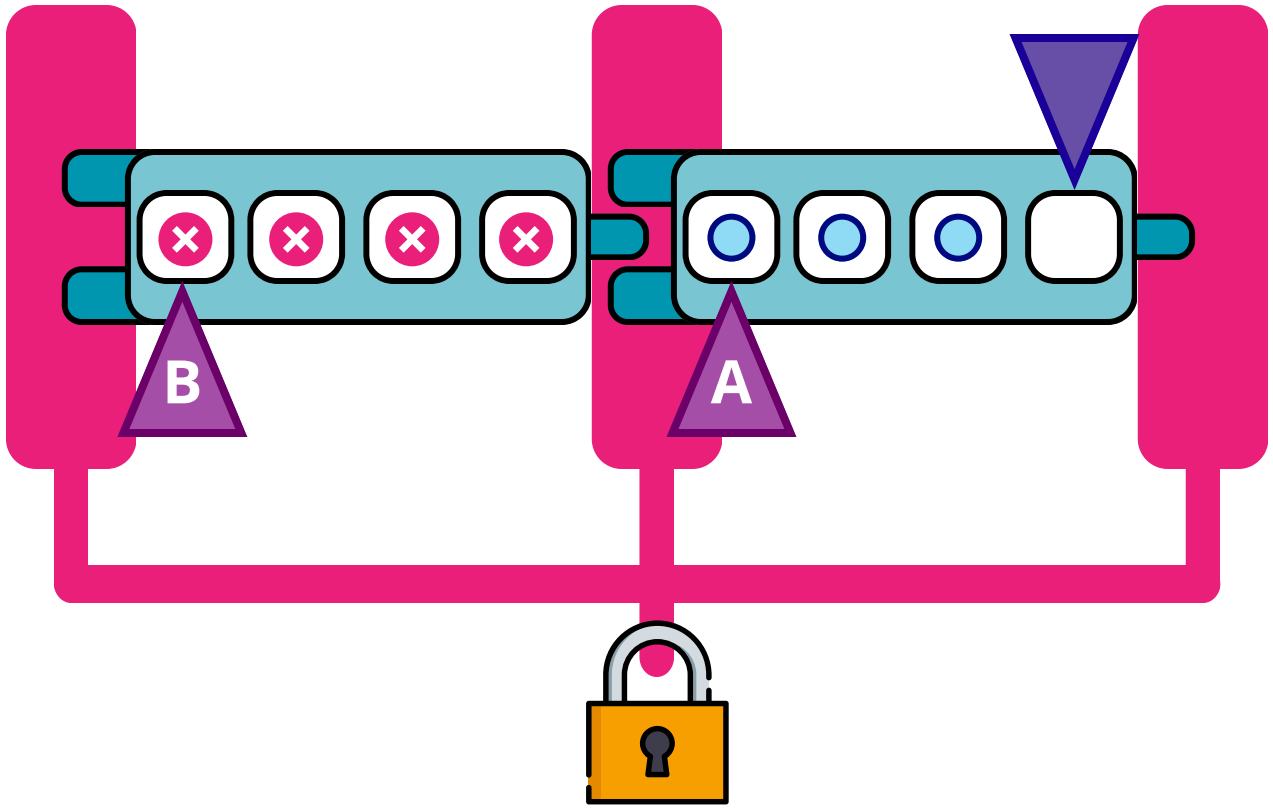
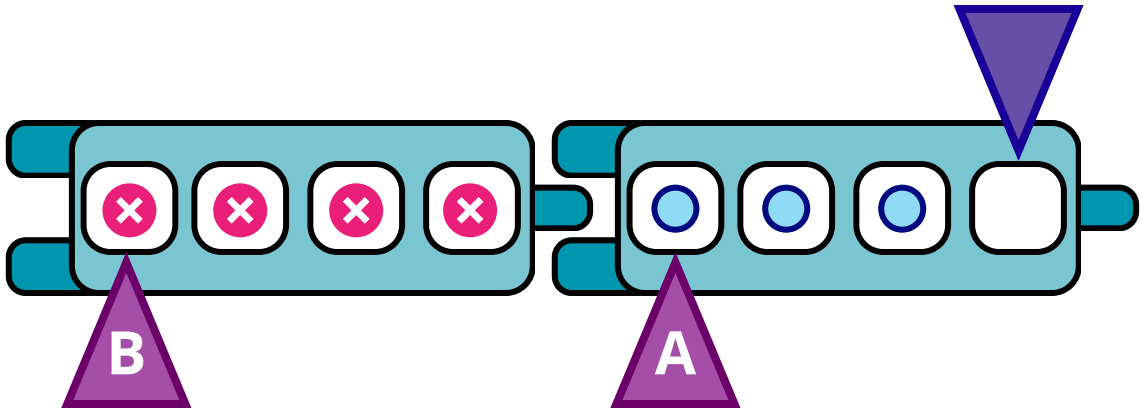
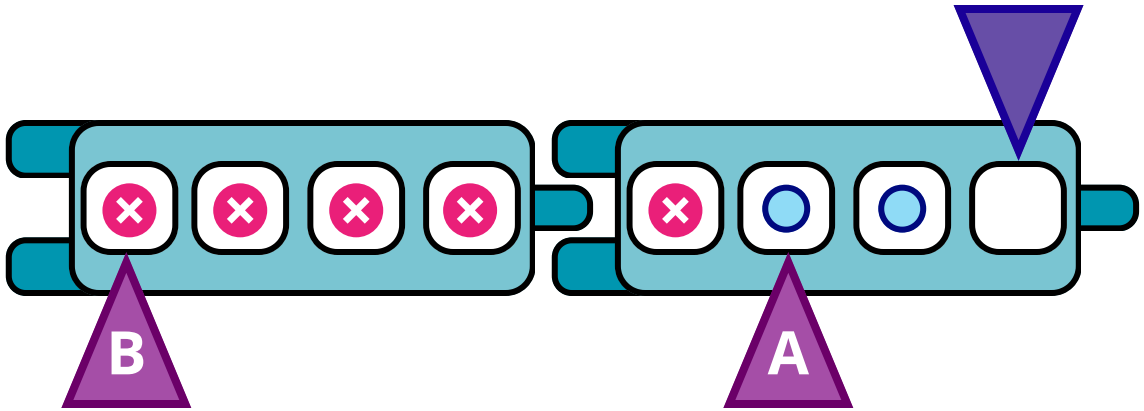


Ready queue example



Ready queue example



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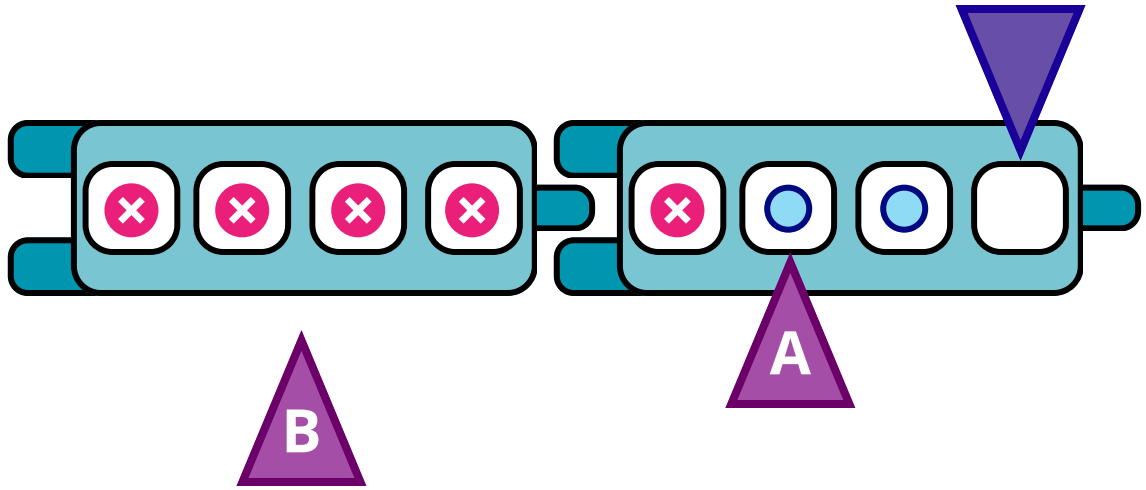
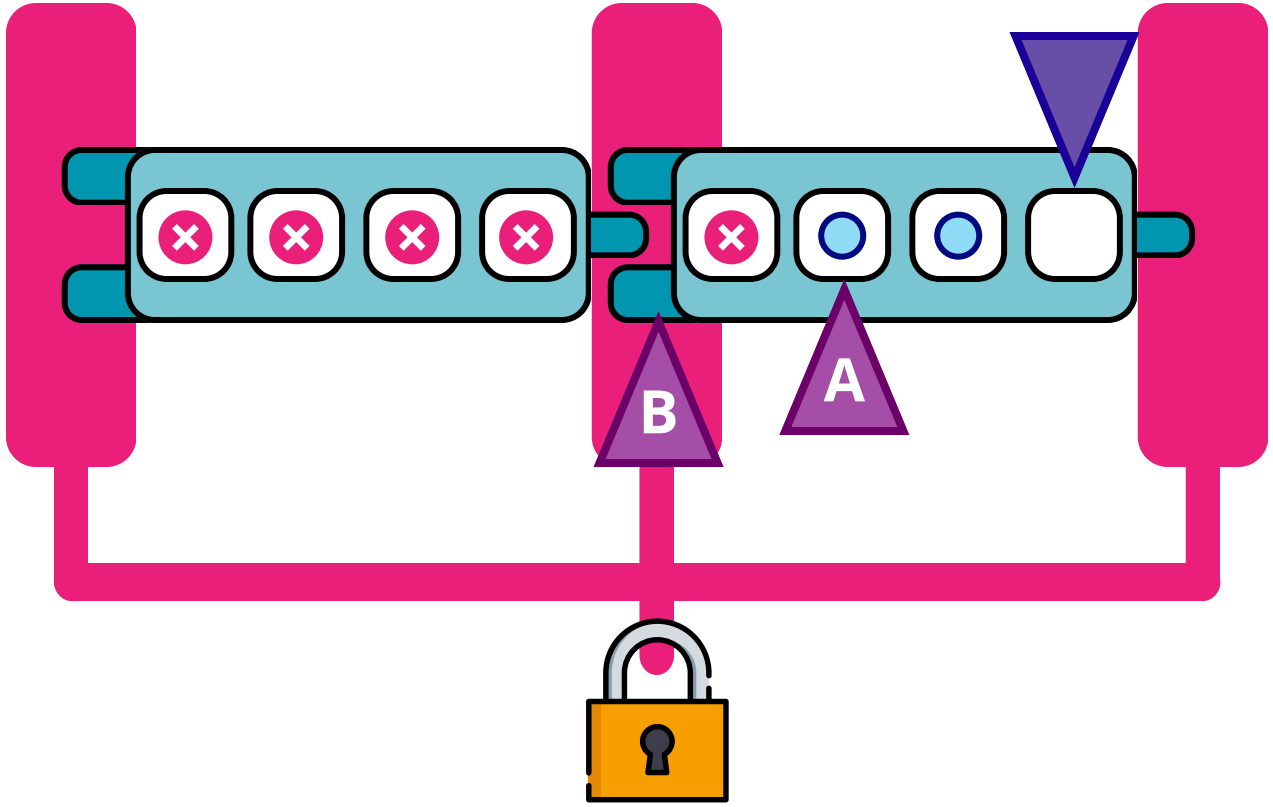
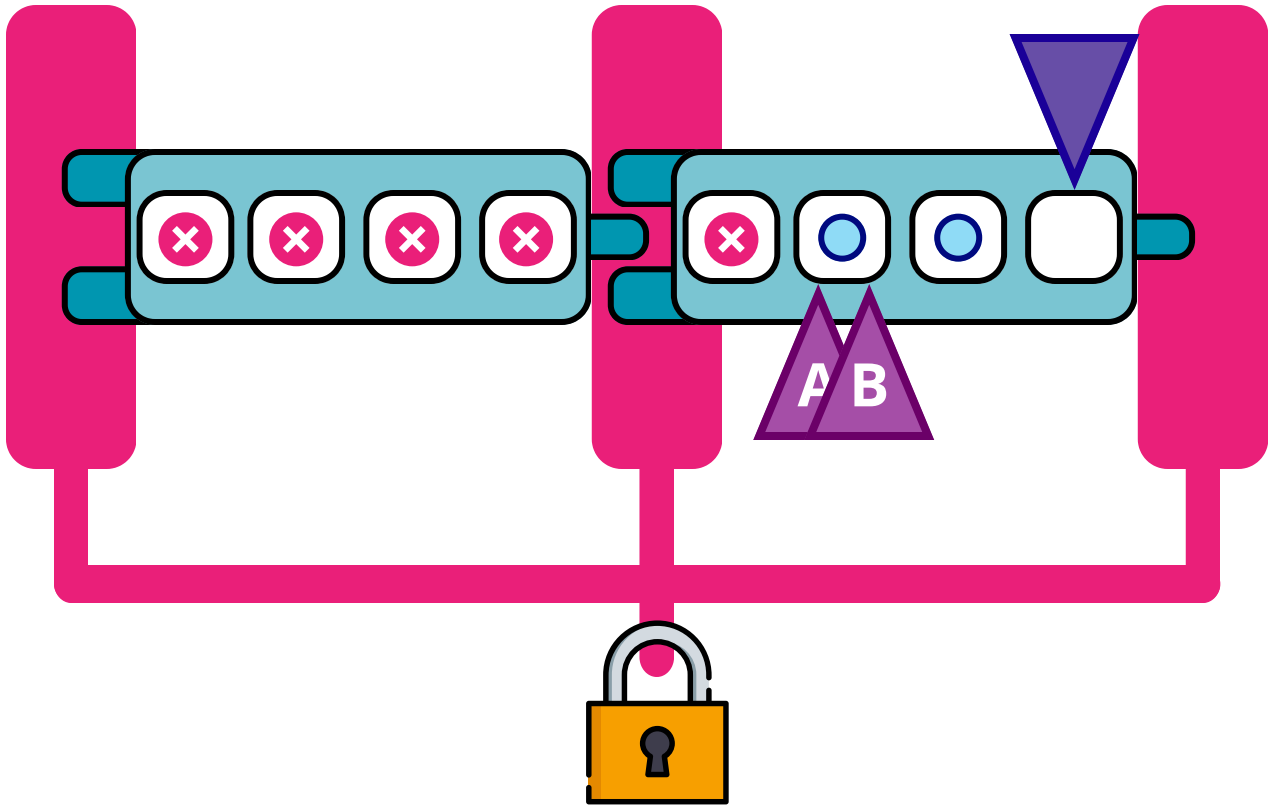


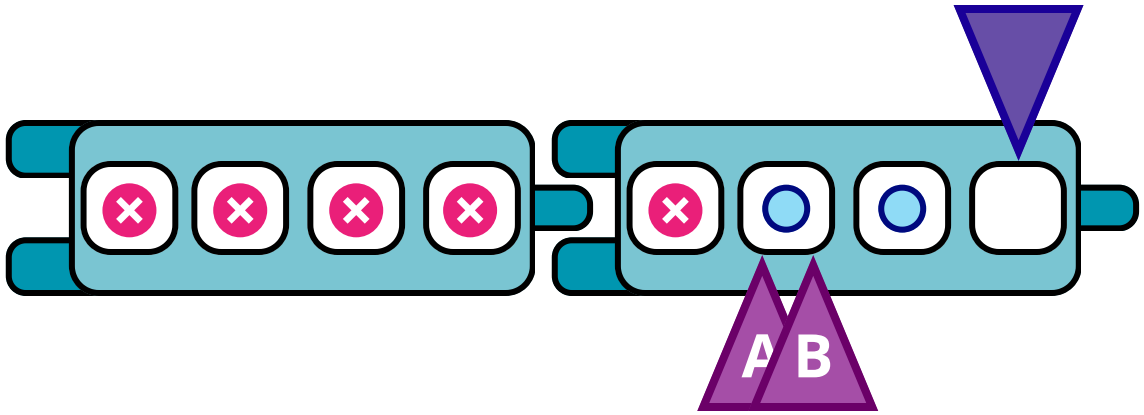
Ready queue example



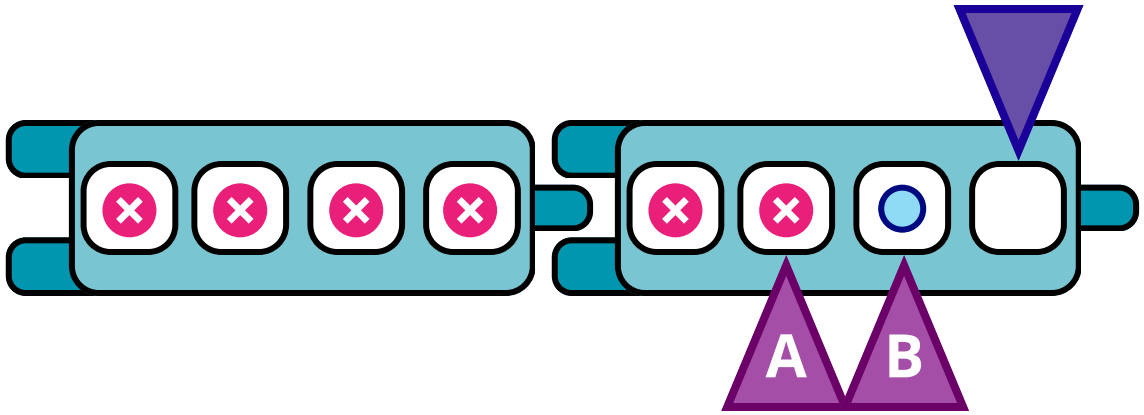
Ready queue example



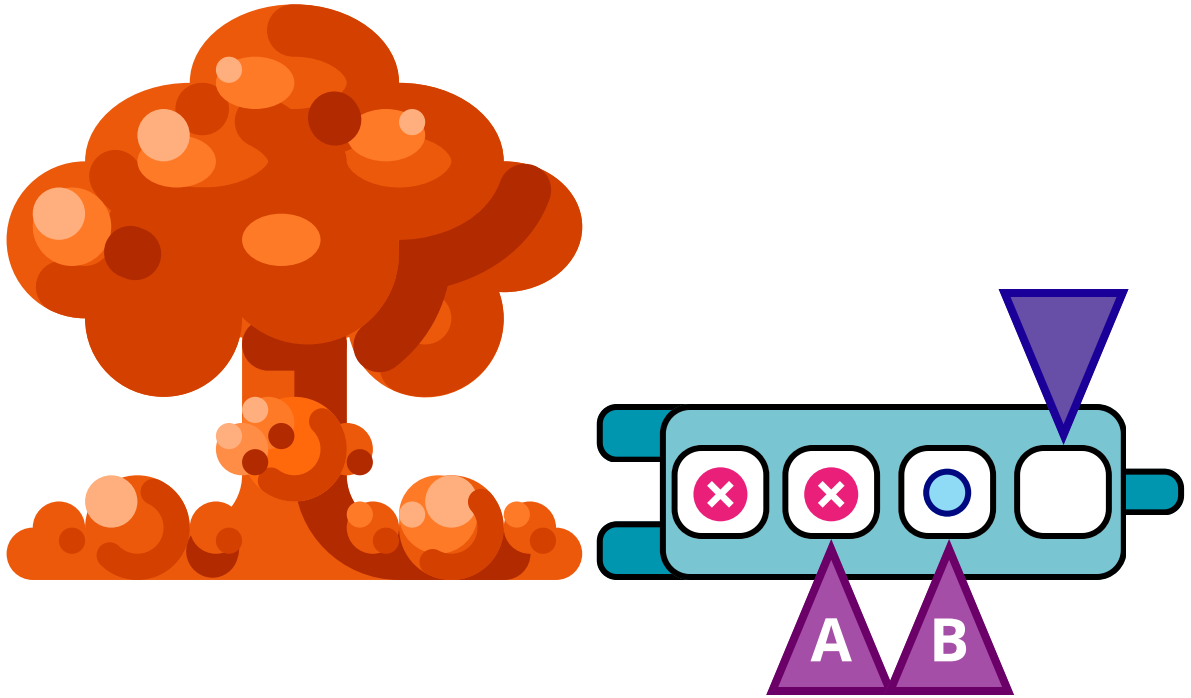
Ready queue example



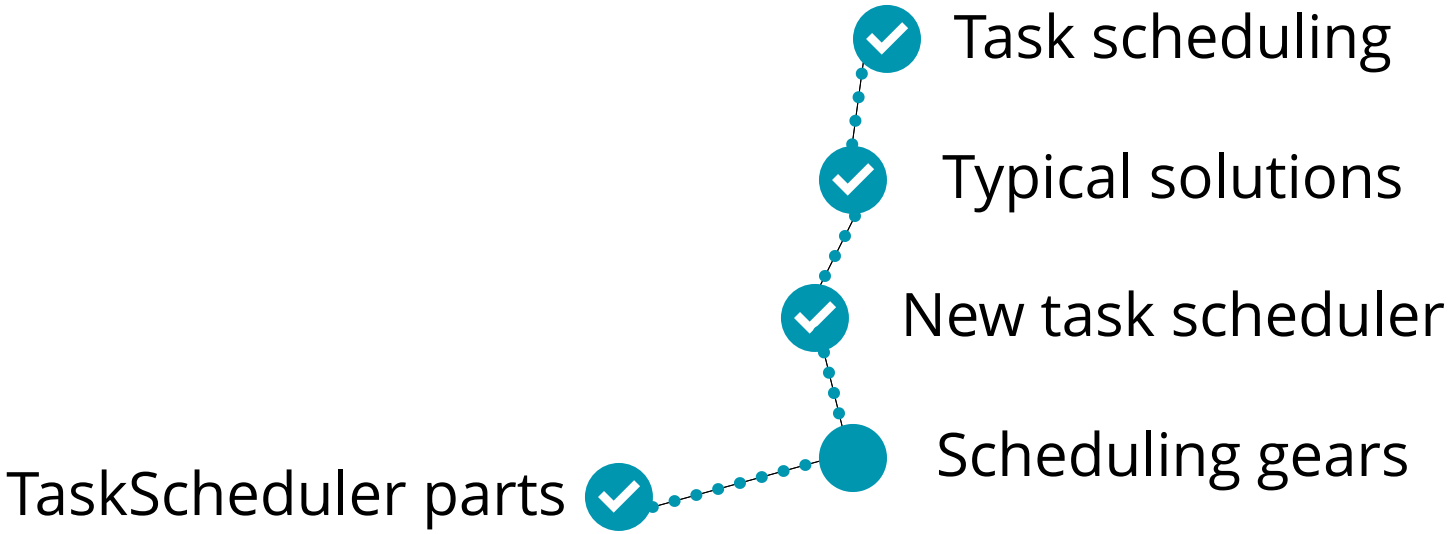
Ready queue example



Ready queue example

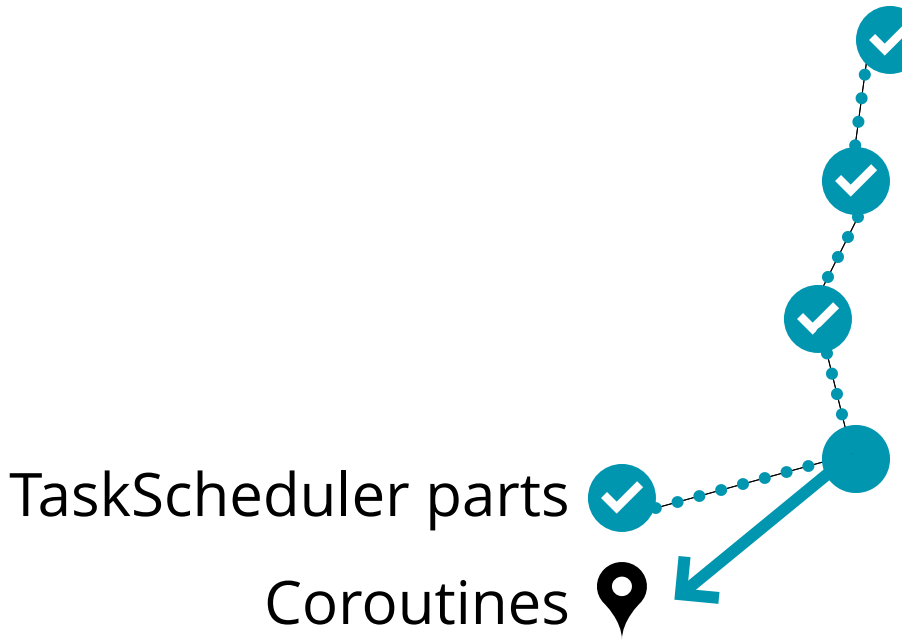


Our progress



- Task scheduling
- Typical solutions
- New task scheduler
- Scheduling gears
- TaskScheduler parts
- Verification
- Benchmarks
- Future plans

Our progress



Task scheduling

Typical solutions

New task scheduler

Scheduling gears

TaskScheduler parts

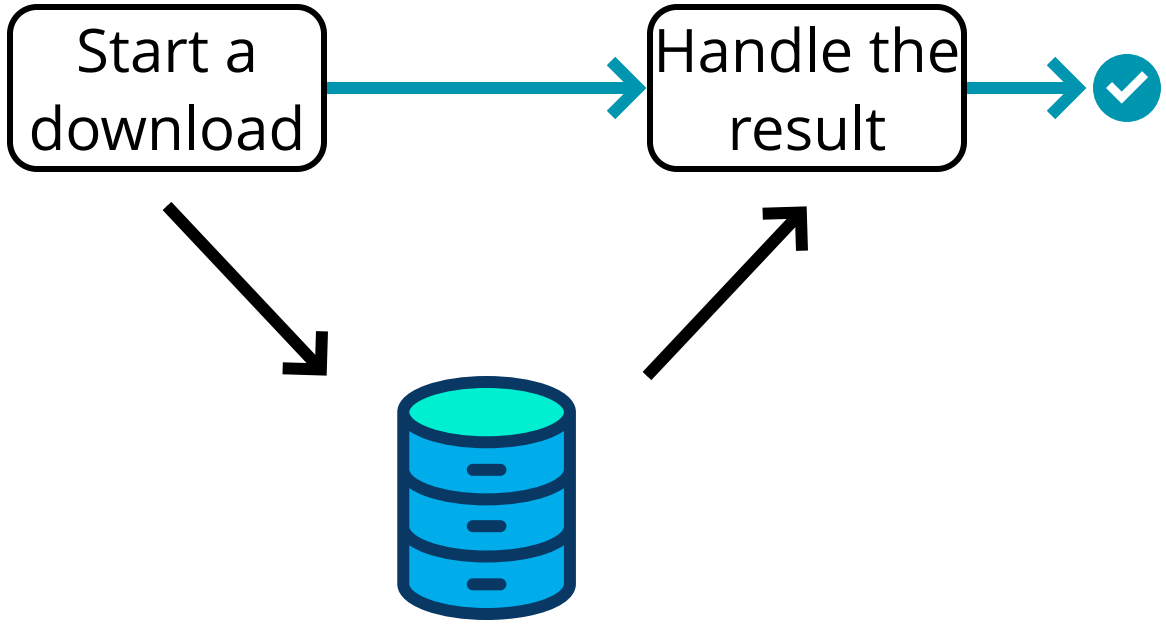
Coroutines

Verification

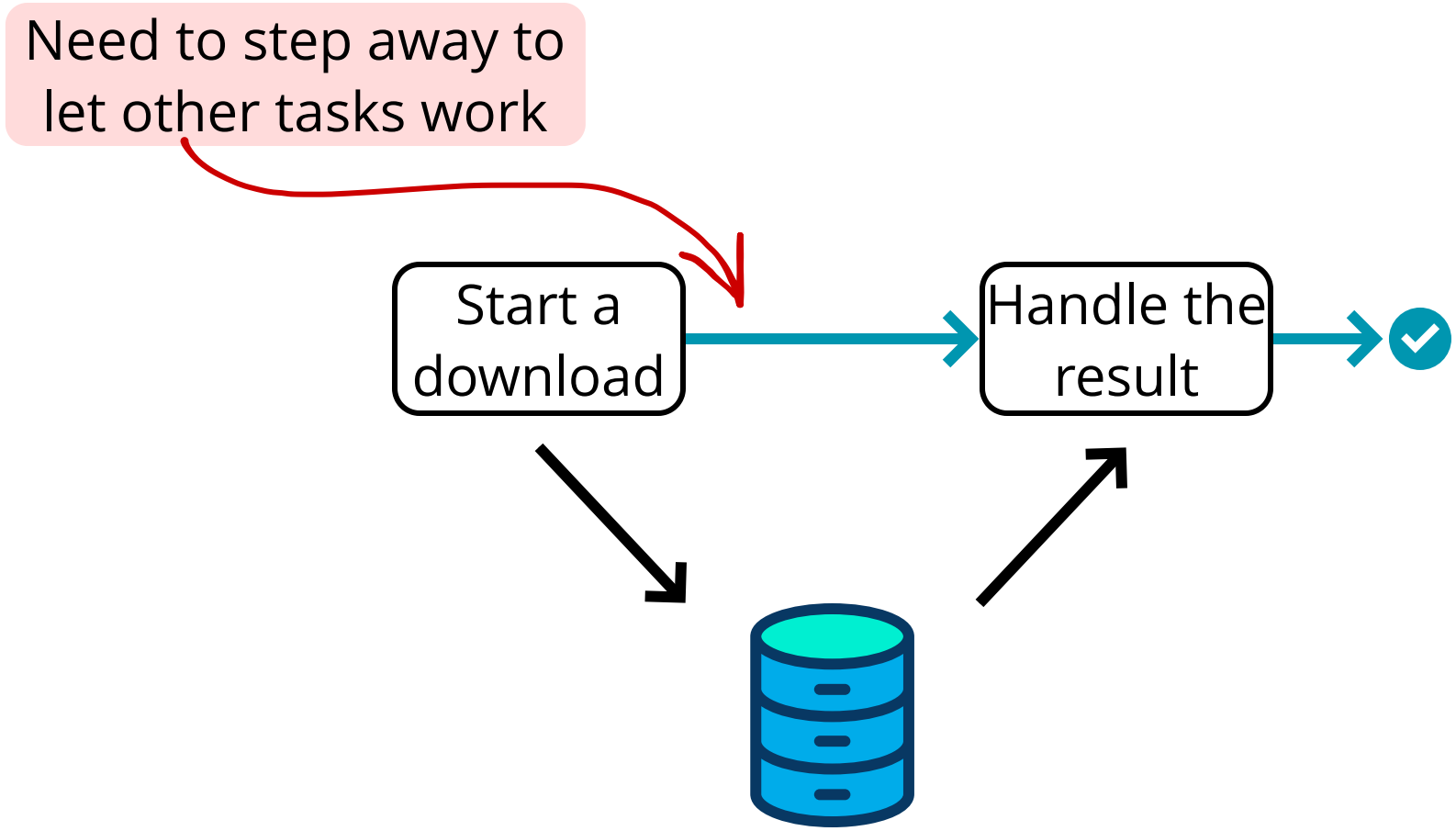
Benchmarks

Future plans

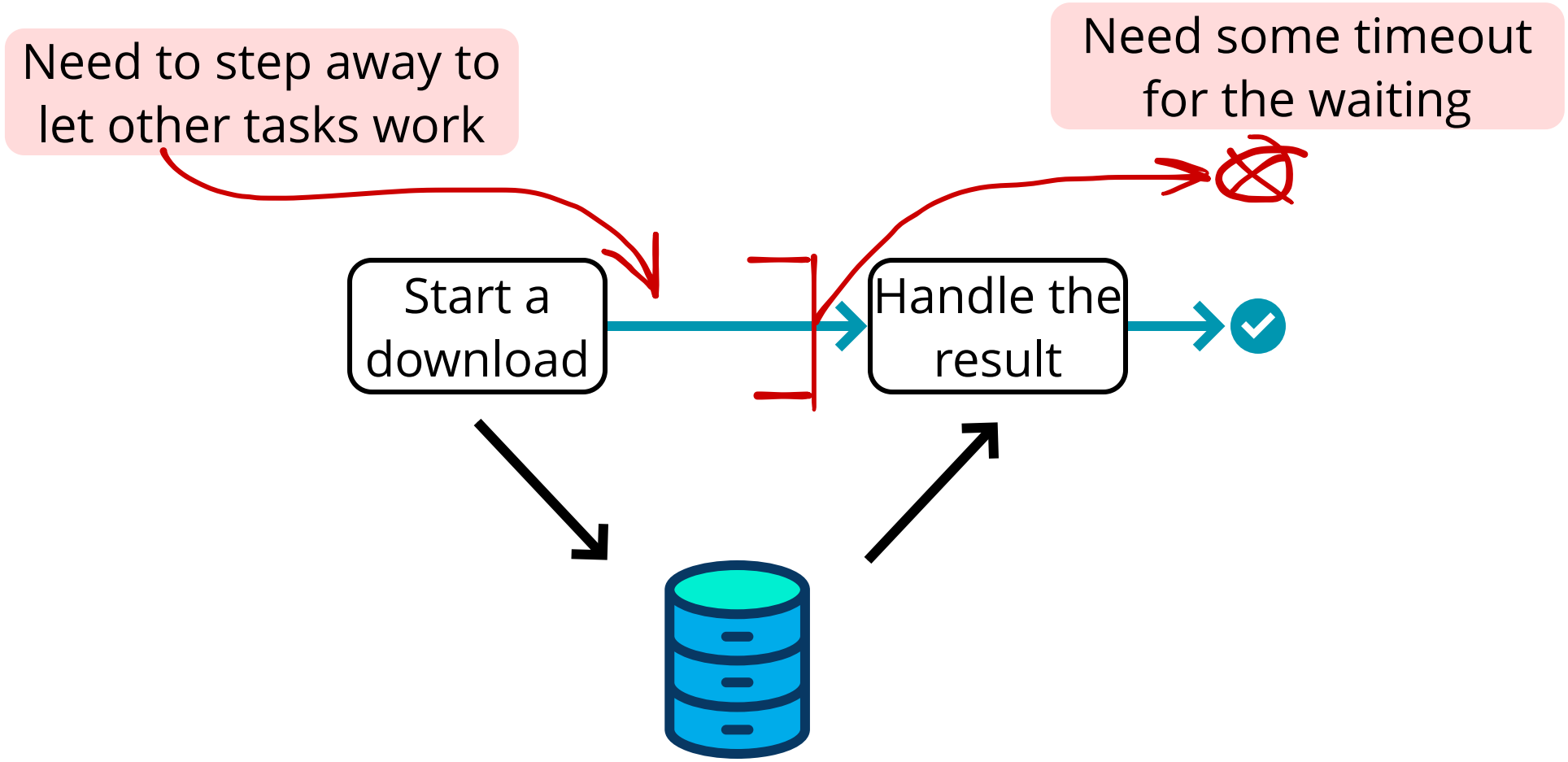
Coroutines



Coroutines


Need to step away to let other tasks work
Start a download
Handle the result

Coroutines


Need to step away to let other tasks work
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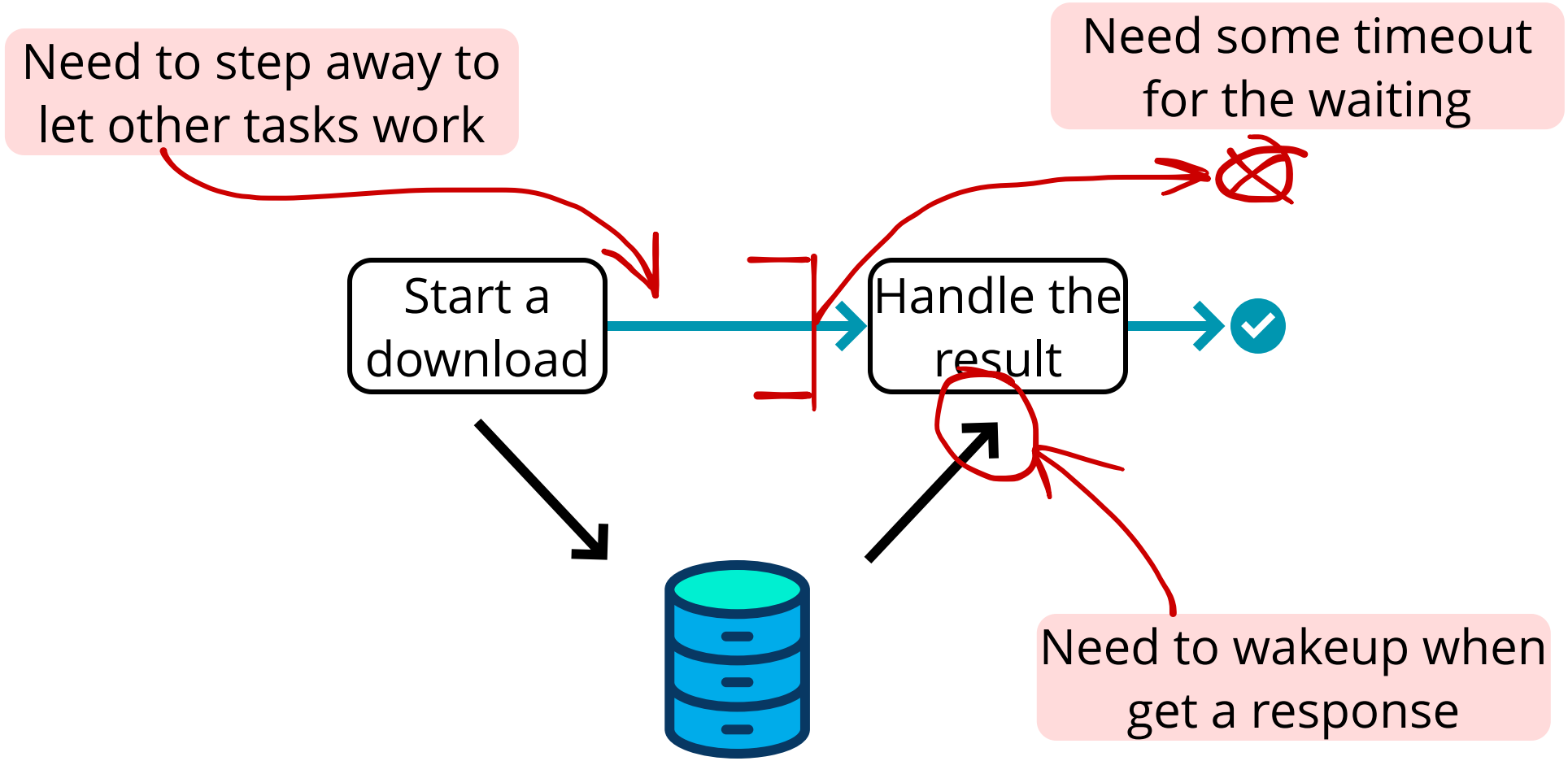
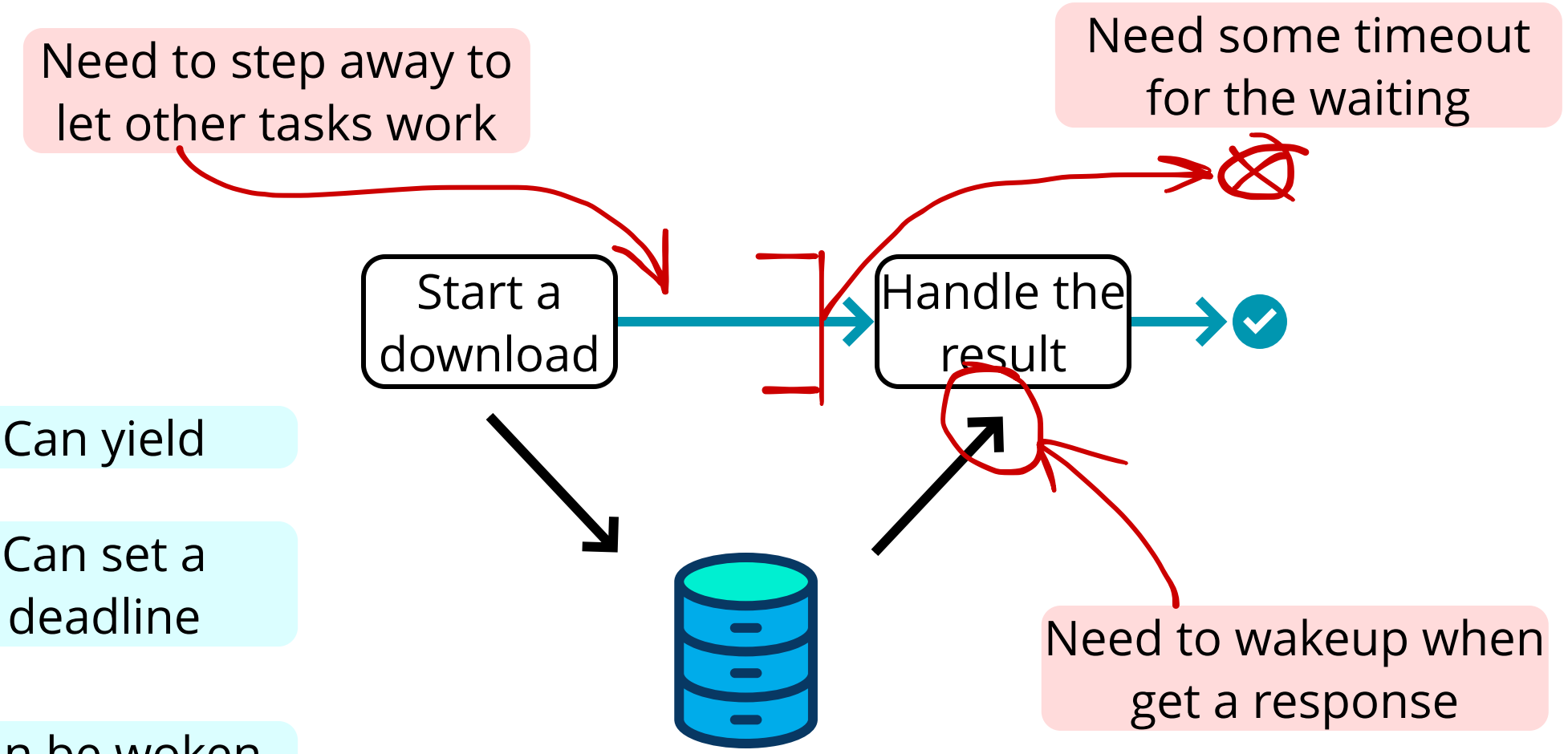
Start a download
Handle the result

Coroutines


Need to step away to let other tasks work
Need some timeout for the waiting
Start a download
Handle the result
Need to wakeup when get a response

Coroutines



Can yield

Can set a deadline

Can be woken up explicitly

Coroutines

```
TaskScheduler sched;
HTTPClient http;
```

Coroutines

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TaskScheduler sched;
HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
sched.Post(t);
```

Coroutines

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HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
sched.Post(t);
```

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url, {
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

Coroutines

```
TaskScheduler sched;
HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
sched.Post(t);
```

Prepare the next step

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url, {
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

Coroutines

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TaskScheduler sched;
HTTPClient http;
```

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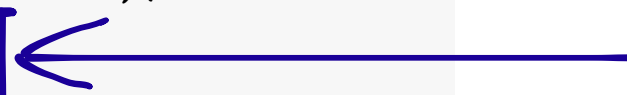

Send an async request, **wakeup()** on completion

Coroutines

```
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HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
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```
Download(t):
    t->SetCallback(HandleResult);
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    });
    sched.PostDeadline(t, now + 5 sec);
```

Yield until +5 secs or wakeup

Coroutines

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TaskScheduler sched;
HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
sched.Post(t);
```

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url, {
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

```
HandleResult(t):
    if (t->IsExpired()) {
        http->Cancel();
        sched.PostWait(t);
        return;
    }
    if (http->IsSuccess())
        HandleSuccess();
    else
        HandleFailure();
    delete t;
```

Coroutines

```
TaskScheduler sched;
HTTPClient http;
```

```
MyTask *t = new MyTask();
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        return;
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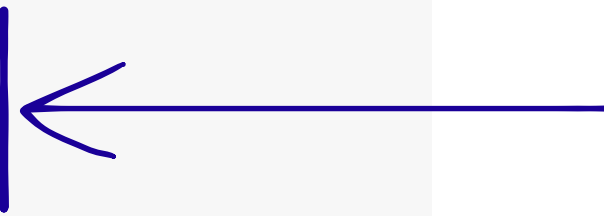
    delete t;
```



Check if the deadline is up. Cancel then

Coroutines

```
TaskScheduler sched;
HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
sched.Post(t);
```

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        return;
    }
    if (http->IsSuccess())
        HandleSuccess();
    else
        HandleFailure();
    delete t;
```

Not expired = completed. Handle it

UBISOFT

Coroutines

```
TaskScheduler sched;
HTTPClient http;
```

```
MyTask *t = new MyTask();
t->SetCallback(Download);
sched.Post(t);
```

```
Download(t):
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HandleResult(t):
    if (t->IsExpired()) {
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        return;
    }
    if (http->IsSuccess())
        HandleSuccess();
    else
        HandleFailure();
    delete t;
```

Completely lock-free, very low overhead

How to verify a multithreaded algorithm?

TLA+ Verification

Temporal **L**ogic of **A**ctions

Language

Math logic with "time" concept

Runtime

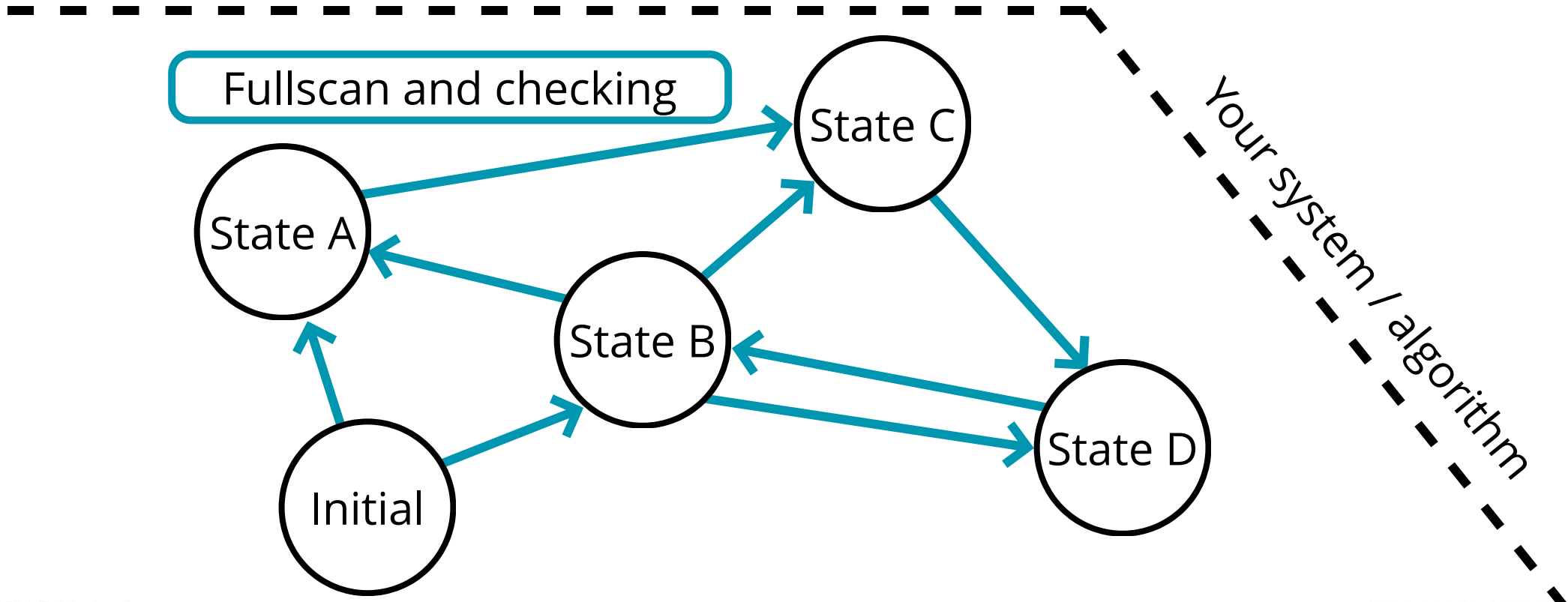
TLA+ Verification

Temporal **L**ogic of **A**ctions

Language

Math logic with "time" concept

Runtime



TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

Decide on **granularity** of the system: **objects**, **actions** on them

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0
```

Actions consist of **conditions**. First is usually "init"

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
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```
Init ==
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  /\ LastSent = 0
```

Actions consist of **conditions**. First is usually "init"

Examples of expressions:

X and Y are true:

```
x /\ y
```

$$X \land Y$$

List of items x, y, z:

```
<<x, y, z>>
```

$$(x, y, z)$$

X equals Y:

```
x = y
```

$$X = Y$$

All items in set Y are equal 10:

```
\A x \in Y: x = 10
```

$$\forall x \in Y : x = 10$$

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
  /\ LastSent < Count
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1
```

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

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  /\ Len(Pipe) < Lim
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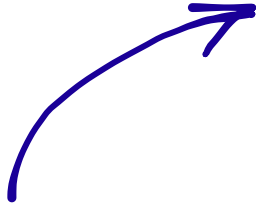
```

Conditions for the action to be possible



TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
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          LastSent
```

```
Init ==
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  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
  /\ LastSent < Count
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1
```

Conditions which "change" the state if the action is possible

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
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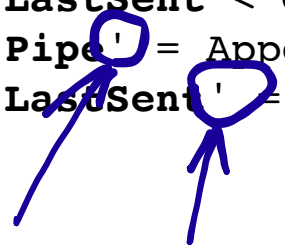
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1
```



Single quote _'_ refers to the next value of the variable

Next value of X equals X + 1:

```
X' = X + 1
```

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
  /\ LastSent < Count
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1

Recv ==
  /\ Len(Pipe) > 0
  /\ LastReceived' = Head(Pipe)
  /\ Pipe' = Tail(Pipe)
```

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
  /\ LastSent < Count
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1

Recv ==
  /\ Len(Pipe) > 0
  /\ LastReceived' = Head(Pipe)
  /\ Pipe' = Tail(Pipe)

PipeInvariant ==
  /\ \A i \in 1..Len(Pipe) - 1: Pipe[i] + 1 = Pipe[i + 1]
  /\ Len(Pipe) =< Lim
  /\ \/ Len(Pipe) = 0
     \/ Pipe[1] = LastReceived + 1
```

TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
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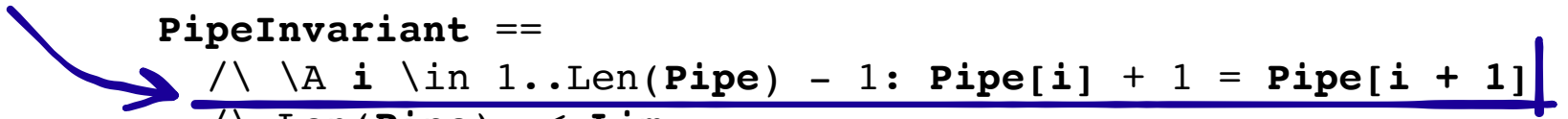
  /\ LastSent < Count
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1

Recv ==
  /\ Len(Pipe) > 0
  /\ LastReceived' = Head(Pipe)
  /\ Pipe' = Tail(Pipe)

PipeInvariant ==
  /\ \A i \in 1..Len(Pipe) - 1: Pipe[i] + 1 = Pipe[i + 1]
  /\ Len(Pipe) =< Lim
  /\ \/ Len(Pipe) = 0
     \/ Pipe[1] = LastReceived + 1
```

Items are ordered



TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

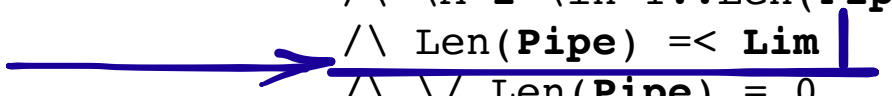
```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
  /\ LastSent < Count
  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1

Recv ==
  /\ Len(Pipe) > 0
  /\ LastReceived' = Head(Pipe)
  /\ Pipe' = Tail(Pipe)

PipeInvariant ==
  /\ \A i \in 1..Len(Pipe) - 1: Pipe[i] + 1 = Pipe[i + 1]
  /\ Len(Pipe) =< Lim
  /\ \/ Len(Pipe) = 0
     \/ Pipe[1] = LastReceived + 1
```

The queue never overflows



TLA+ Example

```
CONSTANT Count
CONSTANT Lim
VARIABLES Pipe,
          LastReceived,
          LastSent
```

```
Init ==
  /\ Pipe = << >>
  /\ LastReceived = 0
  /\ LastSent = 0

Send ==
  /\ Len(Pipe) < Lim
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  /\ Pipe' = Append(Pipe, LastSent + 1)
  /\ LastSent' = LastSent + 1

Recv ==
  /\ Len(Pipe) > 0
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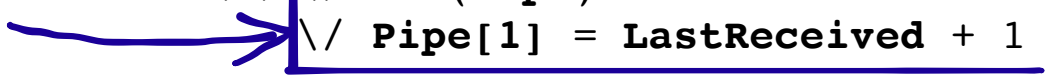
  /\ \A i \in 1..Len(Pipe) - 1: Pipe[i] + 1 = Pipe[i + 1]
  /\ Len(Pipe) =< Lim
  /\ \/ Len(Pipe) = 0
     \/ Pipe[1] = LastReceived + 1
```

The first item is always the next to receive (**or** the queue is empty)



TaskScheduler TLA+

MCSP queue spec: ~430 lines

./tla/MCSPQueue.tla

TaskScheduler spec: ~750 lines

./tla/TaskScheduler.tla

How to **run** it:

./tla/README.md

Study TLA+, great course from its author:

lamport.azurewebsites.net/tla/tla.html

Benchmarks - parts

Benchmarks - parts

Comparative - **algorithm** vs its **naive trivial version**

Benchmarks - parts

Comparative - **algorithm** vs its **naive trivial version**

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading

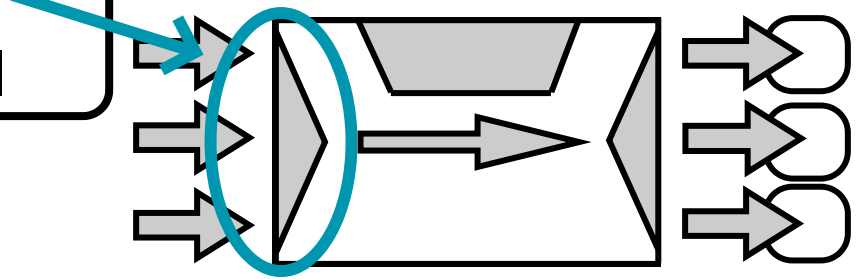
Benchmarks - parts

Comparative - **algorithm** vs its **naive trivial version**

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading

Front Queue

- **5 push**-threads
- **~9 mln/sec**
- **x1.5** faster vs trivial



Benchmarks - parts

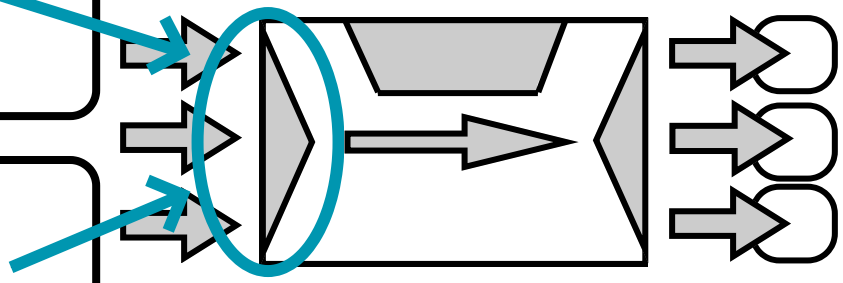
Comparative - **algorithm** vs its **naive trivial version**

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading

Front Queue

- **5 push**-threads
- **~9 mln/sec**
- **x1.5** faster vs trivial

- **10 push**-threads
- **~5.8 mln/sec**
- **x2.6** faster vs trivial



Benchmarks - parts

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Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading

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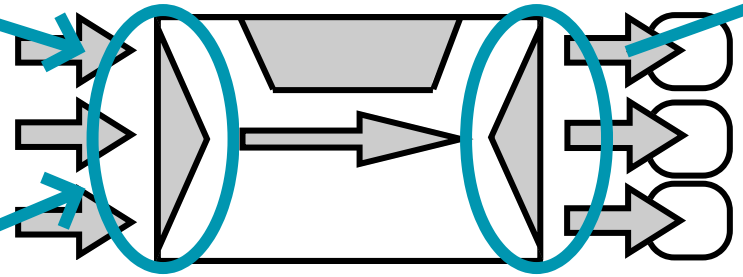


Ready Queue

- **5 pop**-threads
- **~2.5 mln/sec**
- **x2.6 faster** vs trivial
- **x0.0009 lock**-contention

Benchmarks - parts

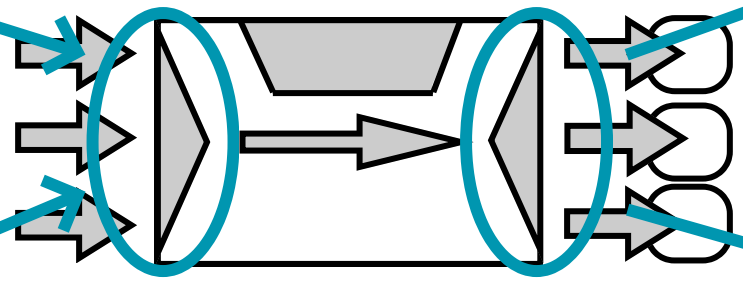
Comparative - **algorithm** vs its **naive trivial version**

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading

Front Queue

- **5 push**-threads
- **~9 mln/sec**
- **x1.5** faster vs trivial

- **10 push**-threads
- **~5.8 mln/sec**
- **x2.6** faster vs trivial



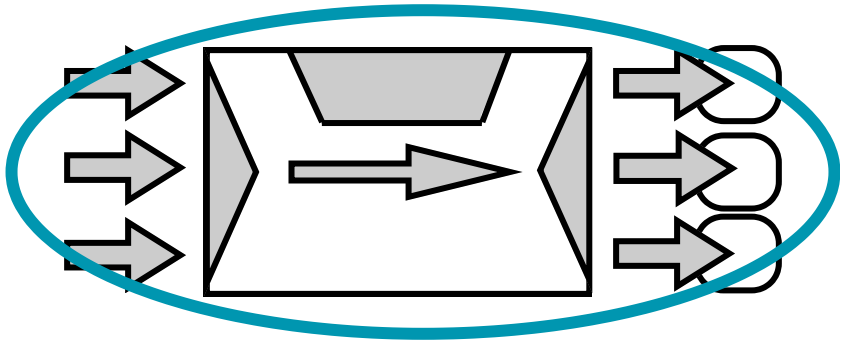
Ready Queue

- **5 pop**-threads
- **~2.5 mln/sec**
- **x2.6 faster** vs trivial
- **x0.0009 lock**-contention

- **10 pop**-threads
- **~1.7 mln tasks/sec**
- **x4.5 faster** vs trivial
- **x0.0007 lock**-contention

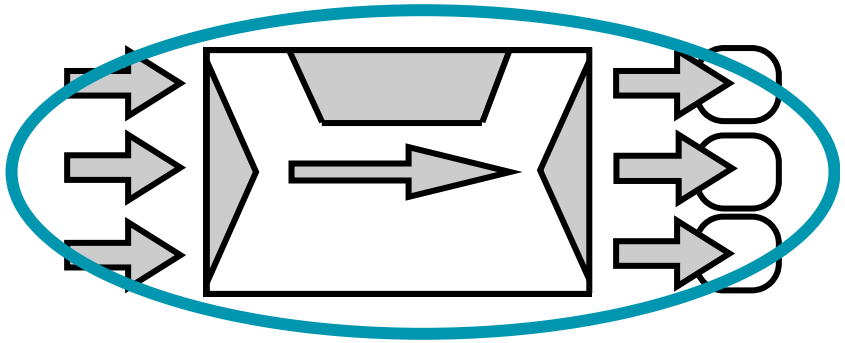
Benchmarks - scheduler

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading



Benchmarks - scheduler

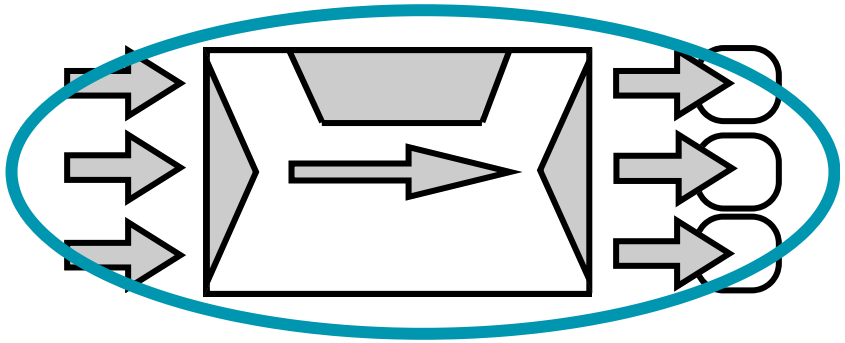
Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading



- **1 worker**
- **~11 mln/sec**
- **x2.2 faster** vs trivial
- **x0 lock**-contention

Benchmarks - scheduler

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading

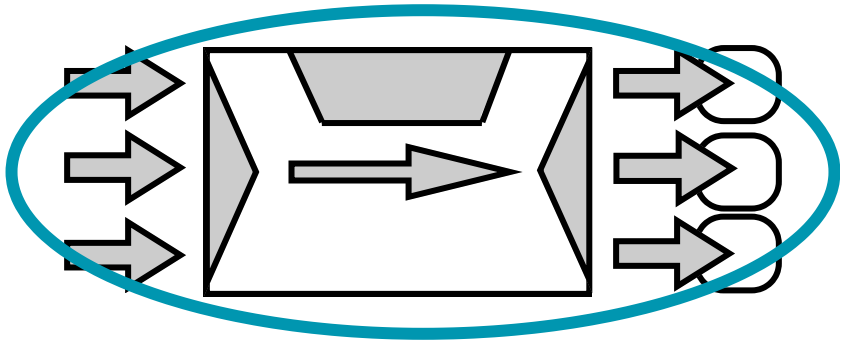


- **1 worker**
- **~11 mln/sec**
- **x2.2 faster** vs trivial
- **x0 lock**-contention

- **5 workers**
- **~4 mln/sec**
- **x3 faster** vs trivial
- **x0.002 lock**-contention

Benchmarks - scheduler

Example: Debian Linux, 8 cores, 2.3GHz, hyperthreading



- **1 worker**
- **~11 mln/sec**
- **x2.2 faster** vs trivial
- **x0 lock**-contention

- **5 workers**
- **~4 mln/sec**
- **x3 faster** vs trivial
- **x0.002 lock**-contention

- **10 workers**
- **~5.2 mln/sec**
- **x7.5 faster** vs trivial
- **x0.003 lock**-contention

Real usage

Savegame blobs multistep processing

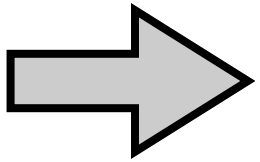
Real usage

Savegame blobs multistep processing

Debian Linux, 8 cores, 2.3GHz, hyperthreading

"Updater":

- **4** workers
- **~100-300** RPS
- **~500** ms latency



x10 speed up right away

"TaskScheduler":

- **4** workers
- **>10000** RPS
- **~100** ms latency

Real usage

Savegame blobs multistep processing

Debian Linux, 8 cores, 2.3GHz, hyperthreading

"Updater":

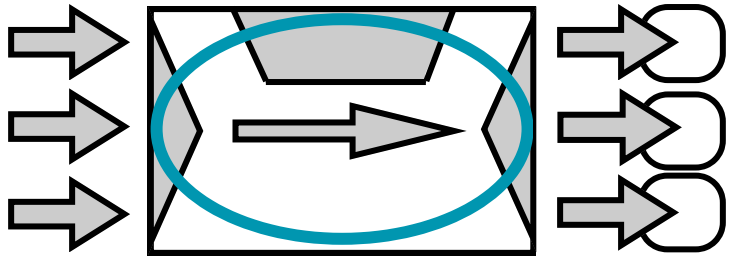
- **4** workers
- **~100-300** RPS
- **~500** ms latency

x10 speed up right away

"TaskScheduler":

- **4** workers
- **>10000** RPS
- **~100** ms latency

The algorithm is extendible



This is a **thread-safe box**. Can do here anything, not just deadlines. Like add **epoll** or **IOCP**

Future plans

Try on ARM

Other languages

Optimizations


The End

The End

TLA+ specs and C++ code:

github.com/ubisoft/task-scheduler

My talks (and this one too):

slides.com/gerold103/taskscheduler-fosdem2023-eng

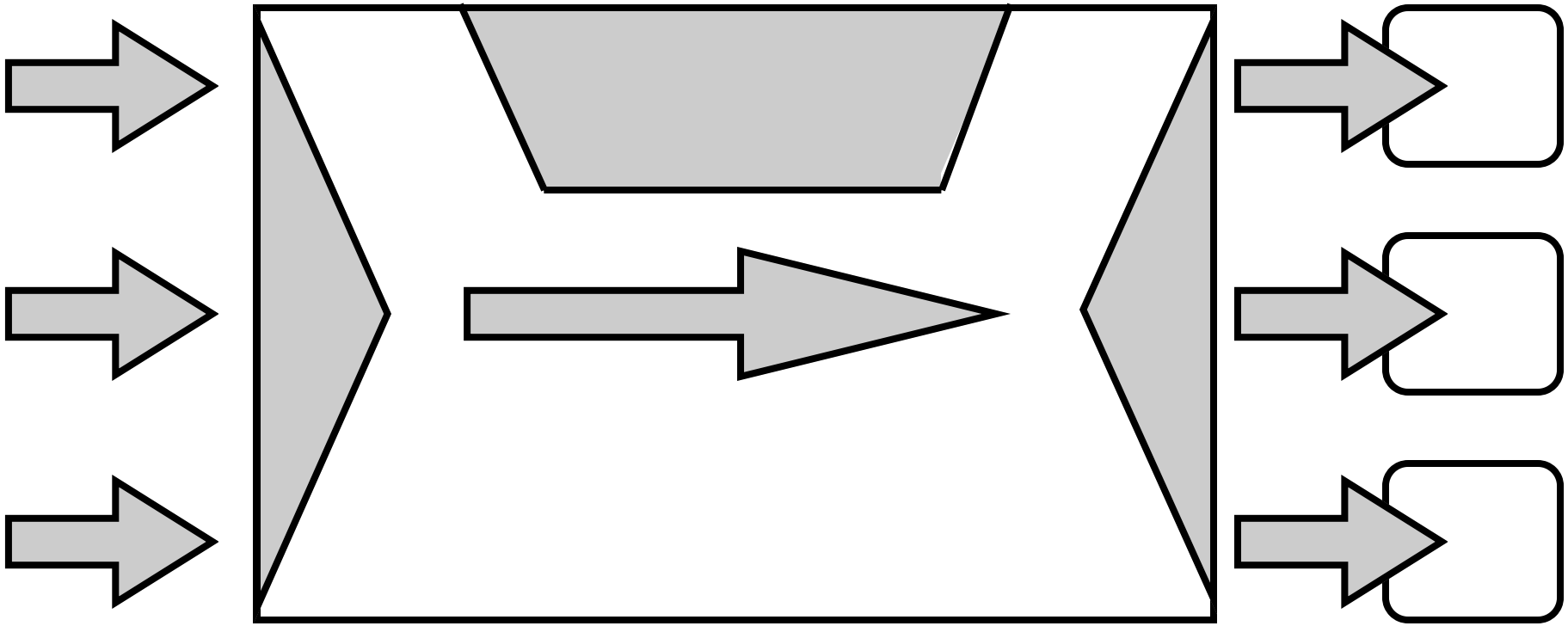
How do the workers **sleep**?

Smart usage of cmpxchg()

Coroutine Wakeup vs **Signal**

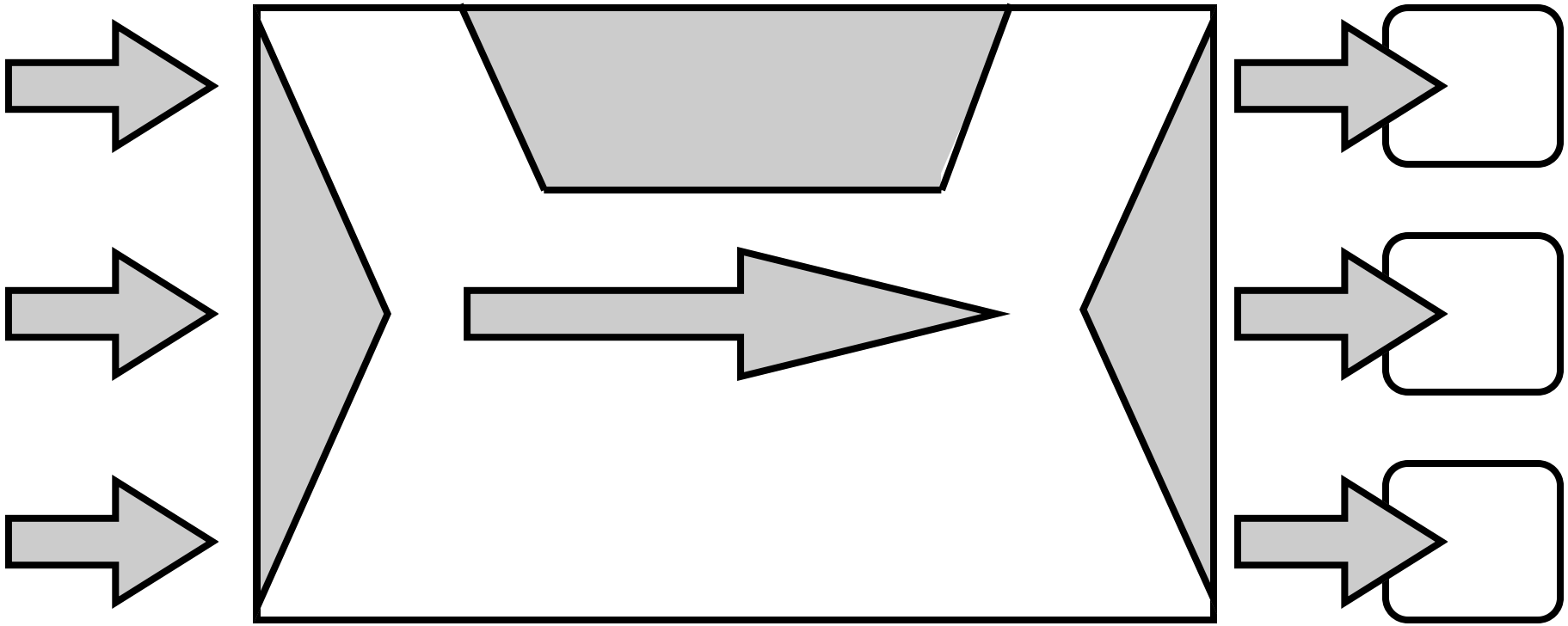
Additional content

Signal



Signal

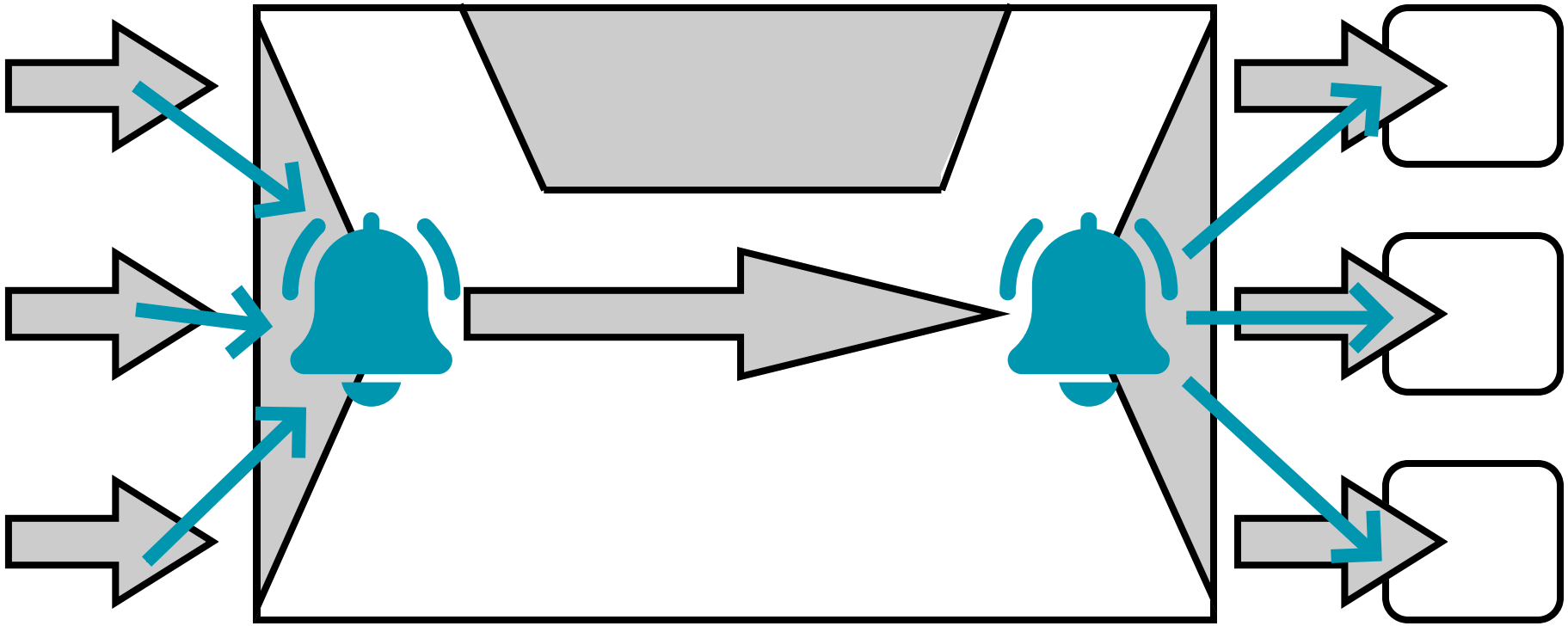
Threads shouldn't **poll**

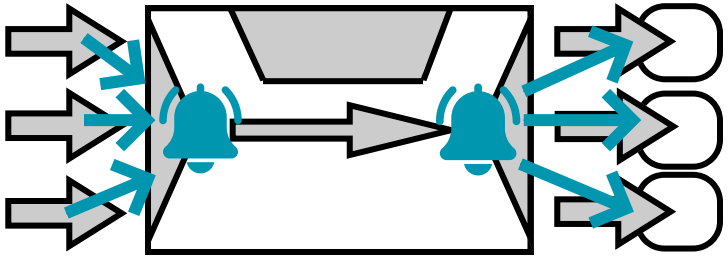


Signal

An event storage

Threads shouldn't **poll**





Signal

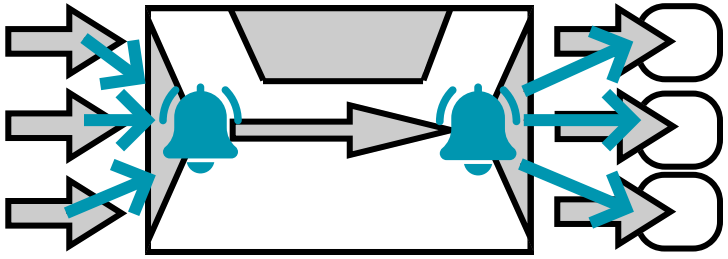
An event storage

Threads shouldn't **poll**

```
Signal sig;
bool hasEvent = false;
```

```
Thread 1:
    hasEvent = true;
    sig.Send();
```

```
Thread 2:
    sig.BlockingReceive()
    assert(hasEvent);
    // Won't receive again:
    assert(sig.IsEmpty());
```



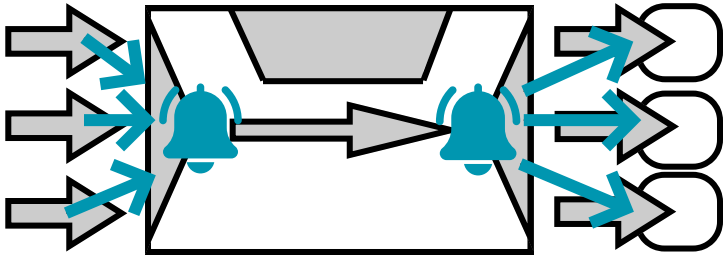
Signal

An event storage

Threads shouldn't **poll**

Usual implementation

```
class Signal:
    Mutex myLock;
    ConditionVariable myCond;
    bool myFlag;
```



Signal

An event storage

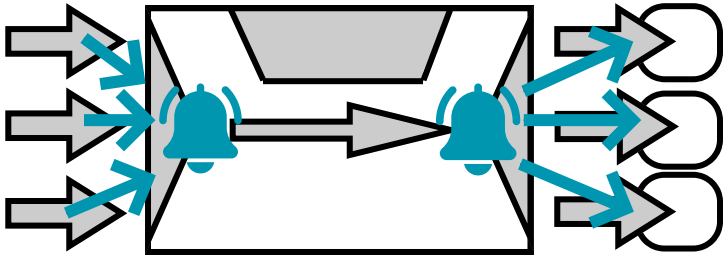
Threads shouldn't **poll**

Usual implementation

```
class Signal:
    Mutex myLock;
    ConditionVariable myCond;
    bool myFlag;
```

```
Signal::Send()
{
    myLock.Lock();
    myFlag = true;
    myCond.Signal();
    myLock.Unlock();
}
```

```
Signal::BlockingReceive()
{
    myLock.Lock();
    while (not myFlag)
        myCond.Wait();
    myFlag = false;
    myLock.Unlock();
}
```



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Threads shouldn't **poll**

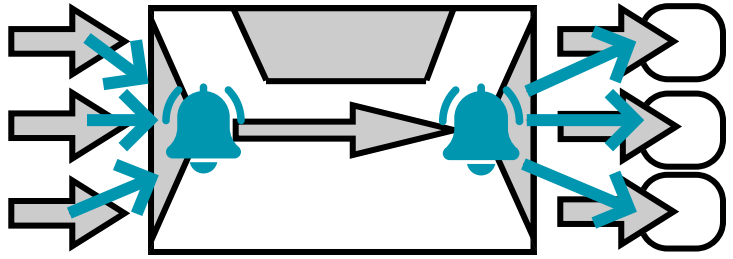
Usual implementation

```
class Signal:
    Mutex myLock;
    ConditionVariable myCond;
    bool myFlag;
```

```
Signal::Send()
{
    myLock.Lock();
    myFlag = true;
    myCond.Signal();
    myLock.Unlock();
}
```

Expensive **mutex lock** on each operation

```
Signal::BlockingReceive()
{
    myLock.Lock();
    while (not myFlag)
        myCond.Wait();
    myFlag = false;
    myLock.Unlock();
}
```



Signal

An event storage

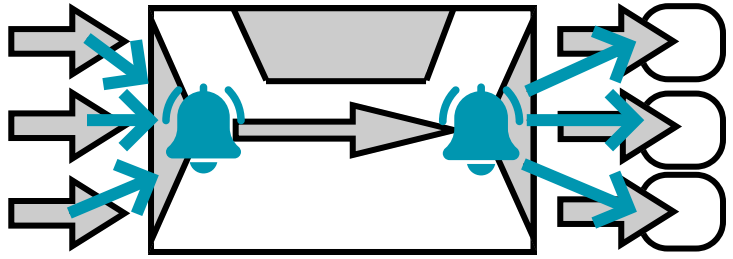
Threads shouldn't **poll**

Lock-free receipt if already signaled

```
class Signal:
    Mutex myLock;
    ConditionVariable myCond;
    bool myFlag;
```

```
Signal::Send()
{
    myLock.Lock();
    AtomicExchange(myFlag, true);
    myCond.Signal();
    myLock.Unlock();
}
```

```
Signal::BlockingReceive()
{
    if (AtomicExchange(myFlag, false))
        return;
    myLock.Lock();
    while (not AtomicExchange(myFlag, false))
        myCond.Wait();
    myLock.Unlock();
}
```



Signal

An event storage

Threads shouldn't **poll**

Lock-free receipt if already signaled

Lock-free send if already signaled

```
class Signal:
    Mutex myLock;
    ConditionVariable myCond;
    bool myFlag;
```

```
Signal::Send()
{
    if (AtomicExchange(myFlag, true))
        return;
    myLock.Lock();
    myCond.Signal();
    myLock.Unlock();
}
```

```
Signal::BlockingReceive()
{
    if (AtomicExchange(myFlag, false))
        return;
    myLock.Lock();
    while (not AtomicExchange(myFlag, false))
        myCond.Wait();
    myLock.Unlock();
}
```

UBISOFT

Back

FOSDEM'23

Smart usage of cmpxchg

```
AtomicCompareExchange(var, new_value, check)
{
    if (old_value == check)
        return false;
    var = new_value;
    return true;
}
```

Smart usage of cmpxchg

```
AtomicCompareExchangeGetOld(var, new_value, check)
{
    if (old_value == check)
        return old_value;
    var = new_value;
    return old_value;
}
```

Smart usage of cmpxchg

```
AtomicCompareExchangeGetOld(var, new_value, check)
{
    if (old_value == check)
        return old_value;
    var = new_value;
    return old_value;
}
```

```
AtomicCompareExchange(var, new_value, check)
{
    return AtomicCompareExchangeGetOld(
        val, new_value, check) == check;
}
```

Smart usage of cmpxchg

```
class MPSCQueue:
    T* myTop;
```

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    do {
        oldTop = AtomicLoad(myTop);
        aItem->myNext = oldTop;
    } while (not AtomicCompareExchange(
        myTop, aItem, oldTop));
}

MPSCQueue::PopAll(T* aItem)
{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Smart usage of cmpxchg

```
class MPSCQueue:
    T* myTop;
```

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    do {
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        aItem->myNext = oldTop;
    } while (not AtomicCompareExchange(
        myTop, aItem, oldTop));
}

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{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Smart usage of cmpxchg

```
class MPSCQueue:
    T* myTop;
```

Load the top once

Atomically retry setting a new top and getting the old one

```
MPSCQueue::Push(T* aItem)
{
    T* oldTop;
    T* res = AtomicLoad(myTop);
    do {
        oldTop = res;
        aItem->myNext = oldTop;
        res = AtomicCompareExchangeGetOld(myTop, aItem, oldTop);
    } while (res != oldTop);
}

MPSCQueue::PopAll(T* aItem)
{
    T* top = AtomicExchange(myTop, nullptr);
    return ReverseList(top);
}
```

Back

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        http->SetReady();
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

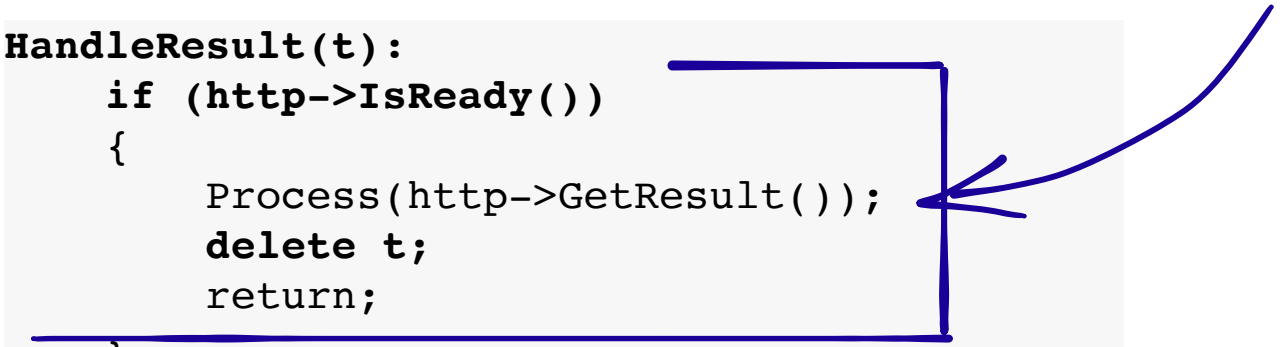
```
HandleResult(t):
    if (http->IsReady())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        http->SetReady();
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

```
HandleResult(t):
    if (http->IsReady())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```



Check the completion before the expiration

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        http->SetReady();
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

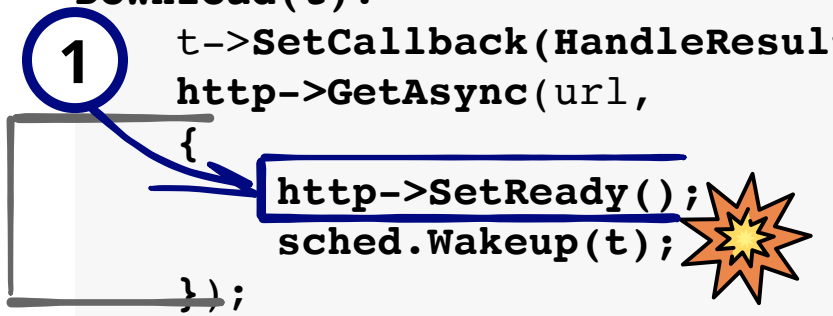
The code will eventually crash here

```
HandleResult(t):
    if (http->IsReady())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

Thread A




```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        http->SetReady();
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

```
HandleResult(t):
    if (http->IsReady())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```

HTTP threads set 'ready' flag

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

Thread A

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        http->SetReady();
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

1

Thread B

```
HandleResult(t):
    if (http->IsReady())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```

2

Scheduler thread wakes up by timeout and deletes the task

Task signal

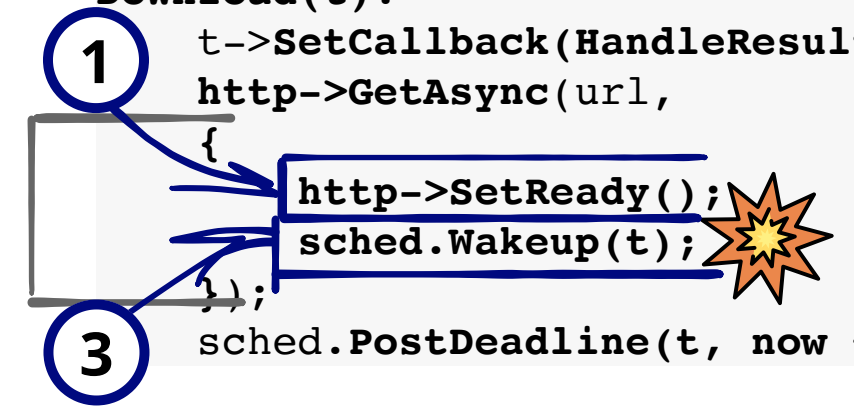
```
TaskScheduler sched;
HTTPClient http;
```

Thread A

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        http->SetReady();
        sched.Wakeup(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

Thread B

```
HandleResult(t):
    if (http->IsReady())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```



HTTP thread uses a deleted task

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        sched.Signal(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

```
HandleResult(t):
    if (t->ReceiveSignal())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```

Task signal

```
TaskScheduler sched;
HTTPClient http;
```

Signal is atomic
"wakeup + set flag"

```
Download(t):
    t->SetCallback(HandleResult);
    http->GetAsync(url,
    {
        sched.Signal(t);
    });
    sched.PostDeadline(t, now + 5 sec);
```

```
HandleResult(t):
    if (t->ReceiveSignal())
    {
        Process(http->GetResult());
        delete t;
        return;
    }
    http->Cancel();
    sched.PostWait(t);
```

Back