Embedded Software

Thread synchronization

Agenda

- Why synchronization - Shared data problem revisited
- Cases
  - Sharing data between threads
  - The Producer / Consumer problem
  - Park-A-Lot 2000
- Types of synchronization methods

The shared data problem revisited

The shared data problem revisited

The shared data problem revisited

```
unsigned int shared;
void taskfunc()
{
   for(;;)
   {
    shared++;                 // Increment i, then wait
    sleep(ONE_SECOND);        // 1 second
   }
}

int main()
{
   shared = 0;
   createThread(taskFunc);  // Start two identical threads
   createThread(taskFunc);  // that run the same function
   for(;;) sleep(ONE_SECOND);      // 1 second
}
```

The shared data problem

Non-interleaved instructions

Interleaved instructions

The shared data problem

Task 1

```
LOAD R1, shared
INC R1
STORE shared, R1
```

Task 2

```
LOAD R1, shared
INC R1
STORE shared, R1
```

Non-interleaved instructions

```
LOAD R1, shared    // shared = 0
INC R1
STORE shared, R1   // shared = 1
LOAD R1, shared    // shared = 1
INC R1
STORE shared, R1   // shared = 2
```

Interleaved instructions

```
LOAD R1, shared    // shared = 0
LOAD R1, shared    // shared = 0
INC R1
STORE shared, R1   // shared = 1
INC R1
STORE shared, R1   // shared = 1
```

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What value is shared suppose to have?

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Which values can shared in fact have?

The shared data problem

Non-interleaved instructions

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The shared data problem

```
Position pos { 10, 20, 30 };
```

Task 1

```
void newPos(Position& ps, float x, float y, float z)
{
  pos.x = x;
  pos.y = y;
  pos.z = z;
}
```

Task 2

```
void printPos(Position& pos)
{
  std::cout << "X: " << pos.x << std::endl;
  std::cout << "Y: " << pos.y << std::endl;
  std::cout << "Z: " << pos.z << std::endl;
}
```

Non-interleaved instructions

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T1  pos.x = x;
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newPos called with 11, 22, 33

Interleaved instructions

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Pseudo'ish code

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T1  pos.y = y;
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Pseudo'ish code

std::cout prints
X: 11
Y: 20
Z: 30

Hey WHAT???

The Challenge

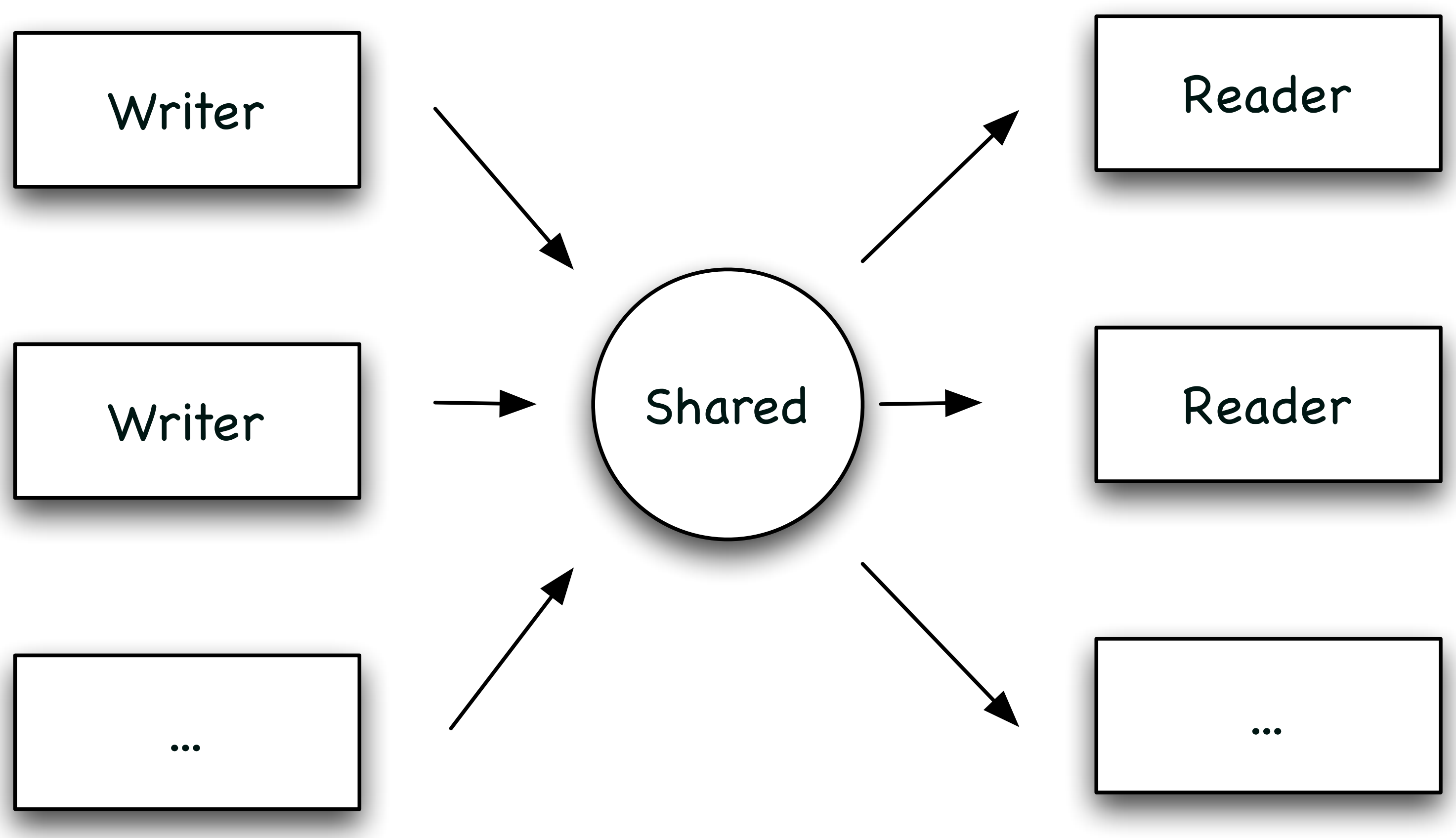
- We need a way to ensure that access to **shared** is mutually exclusive
  - When T_1 is using **shared**, T_2 must be denied access
  - When T_2 is using **shared**, T_1 must be denied access

Cases

Case - Ensuring shared data integrity

Case - Ensuring shared data integrity

- Multiple thread entities read/write to a common data structure (maybe as simple as a single variable)
    - ***Classic problem***



Case - Ensuring shared data integrity

- Problem
  - Common *shared* variable
- Solution “a mutex”

```
unsigned int shared;
Mutex m = MUTEX_INITIALIZER;



void threadFunc()
{
   for(;;)
   {
    lock(m);
    shared++;                  // Increment i...
    unlock(m);
    sleep(ONE_SECOND);         // … then wait 1 second
   }
}

main()
{
   createThread(threadFunc);  // Start two identical threads
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   for(;;) sleep(100);
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```


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The mutex

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The mutex

Take the mutex
(or block if needed)

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Release the mutex

The shared data problem - solution

- Its the programmers responsibility to “lock/unlock” the appropriate places in the code.
- The compiler won’t help you
- Ex. - bad solution

```
void newPos(Position& ps, ...)
{
  pos.x = x;
  lock(m);     // Bad position x is not part
  pos.y = y;
  pos.z = z;
  unlock(m);
}
```

CANNOT be interleaved because of the mutex

The shared data problem - solution

```
Position pos { 10, 20, 30 };
Mutex m;
```

Task 1

```
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}
```

Task 2

```
void printPos(Position& pos)
{
  lock(m);
  std::cout << "X: " << pos.x << std::endl;
  std::cout << "Y: " << pos.y << std::endl;
  std::cout << "Z: " << pos.z << std::endl;
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```
T1  lock(m);
T1  pos.x = x;
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T1  unlock(m);

T2  lock(m);
T2  std::cout << "X: " << pos.x << std::endl;
T2  std::cout << "Y: " << pos.y << std::endl;
T2  std::cout << "Z: " << pos.z << std::endl;
T2  unlock(m);
```

Mutexes

- Mutexes are used to enforce MUTual EXclusion
- Mutexes are owned by one thread at a time - only the “***taker***” can release!
- Two operations on a mutex:
  - **lock(m)**
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```
lock(Mutex m)
{
   wait until m==1, then m=0;  // ATOMIC operation
}
```

If m=0, calling thread is **BLOCKED** until m==1
If m==1, calling thread proceeds

```
unlock(Mutex m)
{
   m=1;  // ATOMIC operation
}
```

Now m==1 so a **BLOCKED** thread
is made **READY**

Case - Ensuring shared data integrity

- Problem
  - Common *shared* variable

- Solution “a semaphore”

```
unsigned int shared;
SEM_ID s;



void threadFunc()
{
   for(;;)
   {
    take(s);
    shared++;                  // Increment i...
    release(s);
    sleep(ONE_SECOND);         // … then wait 1 second
   }
}

main()
{
    s = createSem(1);
   createThread(threadFunc);  // Start two identical threads
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Take the semaphore
(or block if needed)

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Release the semaphore

Initializing the sem to 1

Semaphores

- Semaphores are used to enforce mutual exclusion or rather signaling
- Semaphores are NOT owned by one thread at a time - “***all***” can release!
- Two operations on a semaphore:
  - **take(s)** (A.K.A. get(s), pend(s), P(s), wait(s)…)
  - **release(s)** (A.K.A. give(s), post(s), V(s), signal(s)…)

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```
take(Semaphore s)
{
   wait until s>0, then s=s-1;  // ATOMIC operation
}
```

If s=0, calling thread is **BLOCKED** until s>0
If s>0, calling thread proceeds

```
release(Semaphore s)
{
   s=s+1;  // ATOMIC operation
}
```

Now s>0 so a **BLOCKED** thread
is made **READY**

Mutexes & Semaphores: FAQ

- “Can more than one thread wait for a mutex/semaphore at a time?”
  - Yes. The threads are queued – see next slide

- “Which of the blocked threads are made ready?”
  - FIFO: The thread that has waited the longest
  - Priority: The highest-priority thread

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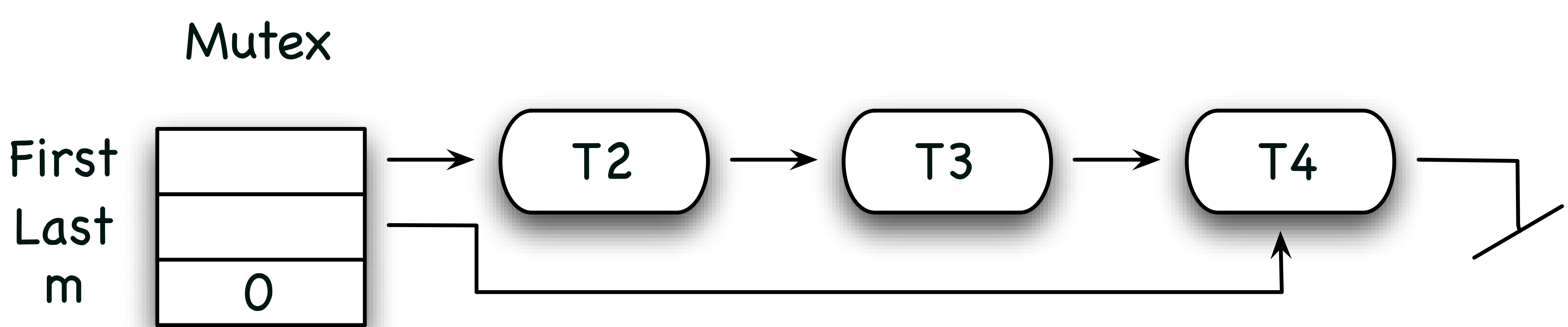
Mutexes & Semaphores: The queue

- Each mutex/semaphore is associated with a waiting queue (FIFO/priority)

- When a thread takes a mutex:
  - m=0: the next incoming thread is added to the mutex's queue
  - m=1: running thread done, next thread activated



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   wait until m==1, then m=0;
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```

```
unlock(Mutex m)
{
   m=1;
}
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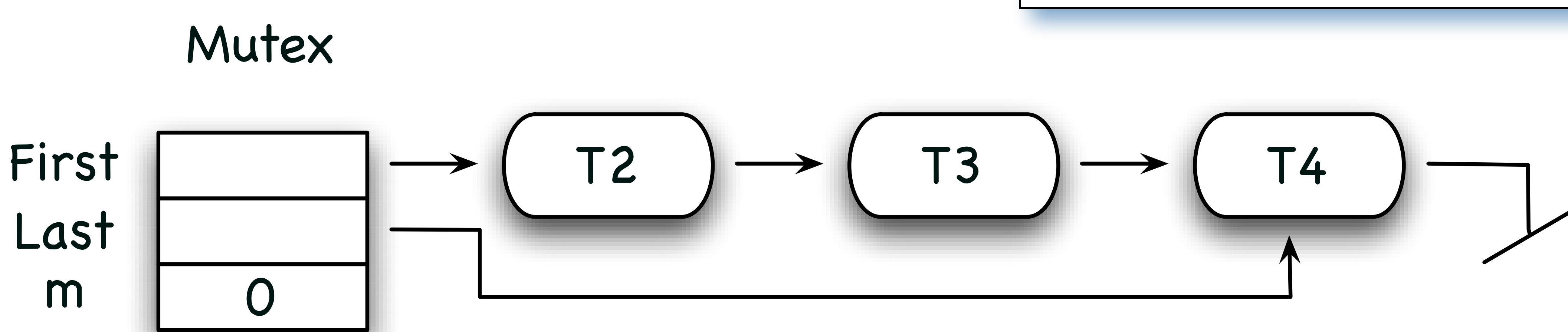

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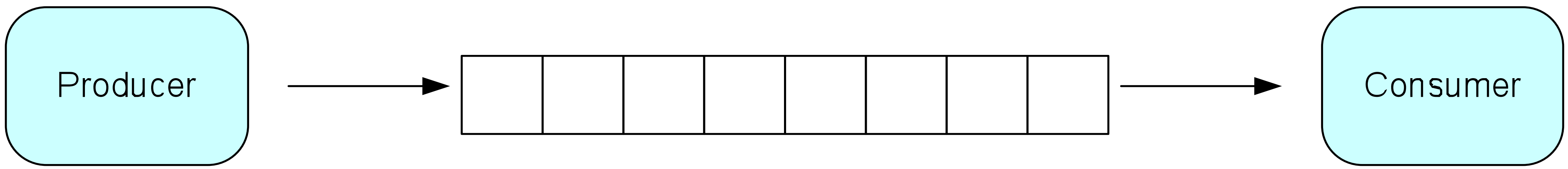
The Producer-Consumer problem

The Producer-Consumer problem

- A producer produces elements and *puts* them in a ***buffer,*** from which the consumer *retrieves* an element at a time



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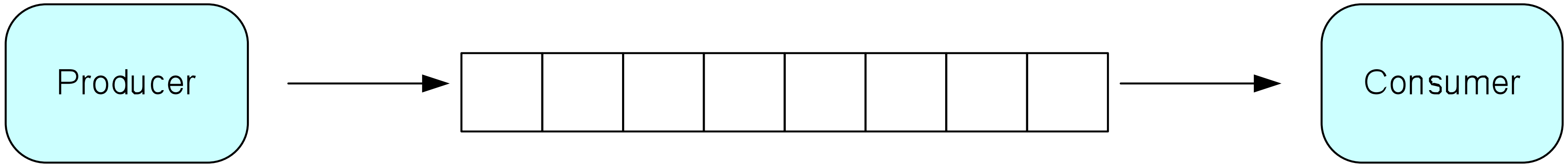

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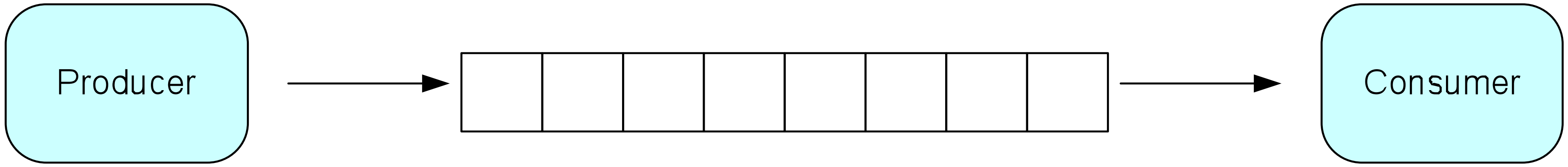
The producer-consumer problem

- What happens if…
  - The producer **put()**'s into a full buffer?
  - The consumer **get()**'s from an empty buffer?



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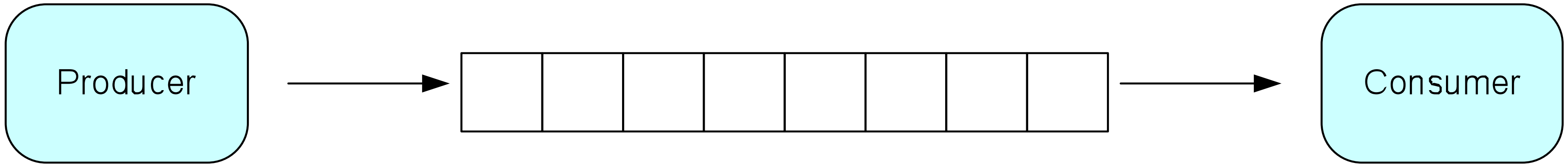

The producer-consumer problem

- What happens if…
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- How can this be handled?
  - Checking **insert** and **remove** before insertion?
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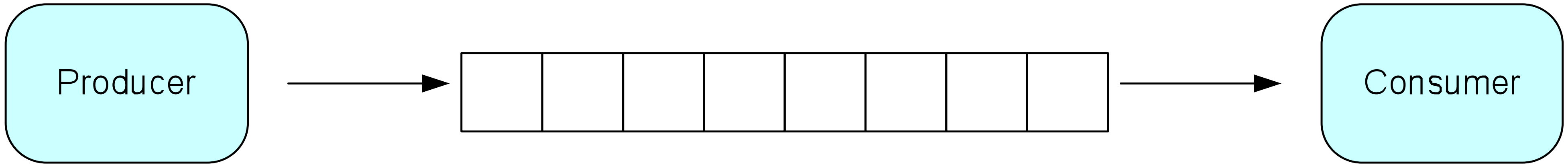
  - Use 2 counting semaphores!



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The producer-consumer problem

- What happens if…
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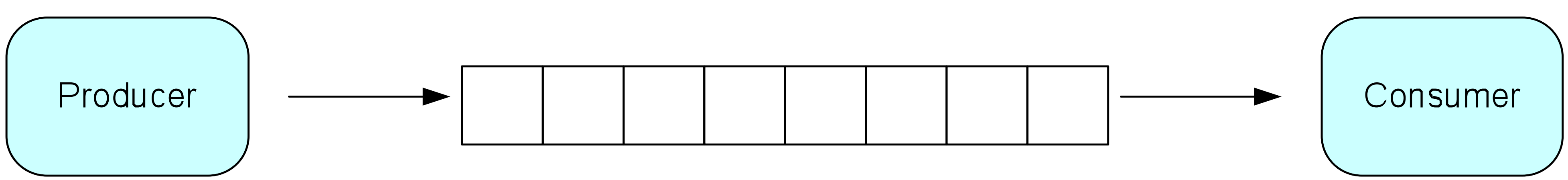

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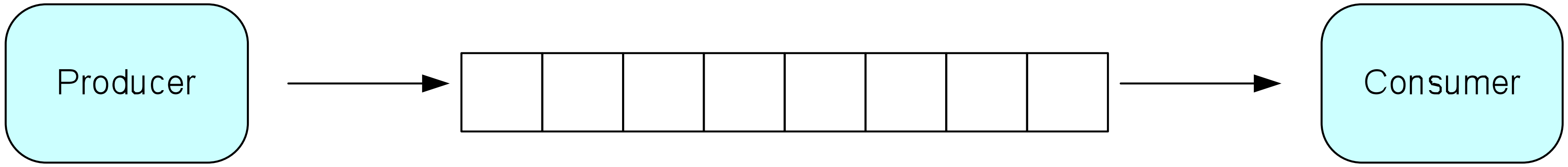

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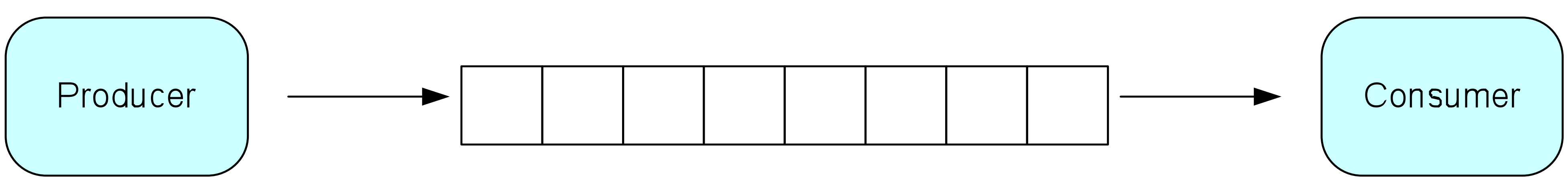

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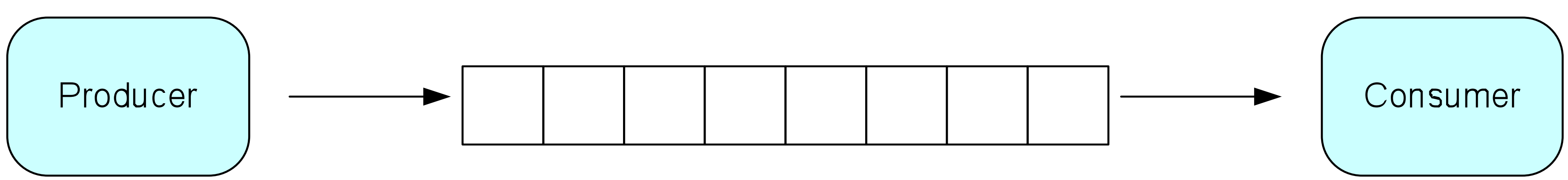

The producer-consumer problem

- ***Explain how to extend this implementation to use 2 counting semaphores to prevent buffer over/underrun***

```
template<typename T>
class Buffer
{
public:
   Buffer(size_t buffserSize) : buffer_(new T[bufferSize]),
   bufferSize_(bufferSize), insert_(0), remove_(0) { }

   void put(const T& x)  {
     buffer_[insert_] = x;
     insert_ = (insert+1)%bufferSize_;
   }

   T get() {
     T tmp = buffer_[remove_];
     remove_ = (remove_+1)%bufferSize_;
     return tmp;
   }

private:
   T* buffer_;
   size_t bufferSize_;
   CountingSemaphore emptySlotsLeft_;
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```

Simplified construction
Possible exceptions are NOT handled

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};
```

Implemented as ***circular buffer***
insert_ : Insertion pointer
remove_ : Remove pointer

Only ***one*** producer & ***one*** consumer

Simplified construction
Possible exceptions are NOT handled

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The producer-consumer problem

```
template<typename T>
class Buffer
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public:
    Buffer(size_t bufferSize) : buffer_(new T[bufferSize]), bufferSize_(bufferSize),
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     emptySlotsLeftSem_ = createCountingSem(bufferSize_);
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    T* buffer_;
    size_t bufferSize_;
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```

Simplified construction
Possible exceptions are NOT handled

Both consumer and producer threads will be **automatically unblocked** if data is ready or buffer not full any longer

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    }

private:
    T* buffer_;
    size_t bufferSize_;
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Semaphores are init with size bufferSize_

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```

Semaphores are init with size bufferSize_

The producer thread will automatically block if buffer is full on **put()**

Both consumer and producer threads will be **automatically unblocked** if data is ready or buffer not full any longer

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```

Semaphores are init with size bufferSize_

The producer thread will automatically block if buffer is full on **put()**

The consumer thread will be automatically blocked if buffer is empty on **get()**

Both consumer and producer threads will be **automatically unblocked** if data is ready or buffer not full any longer

Simplified construction
Possible exceptions are NOT handled

Case - Park-a-lot 2000

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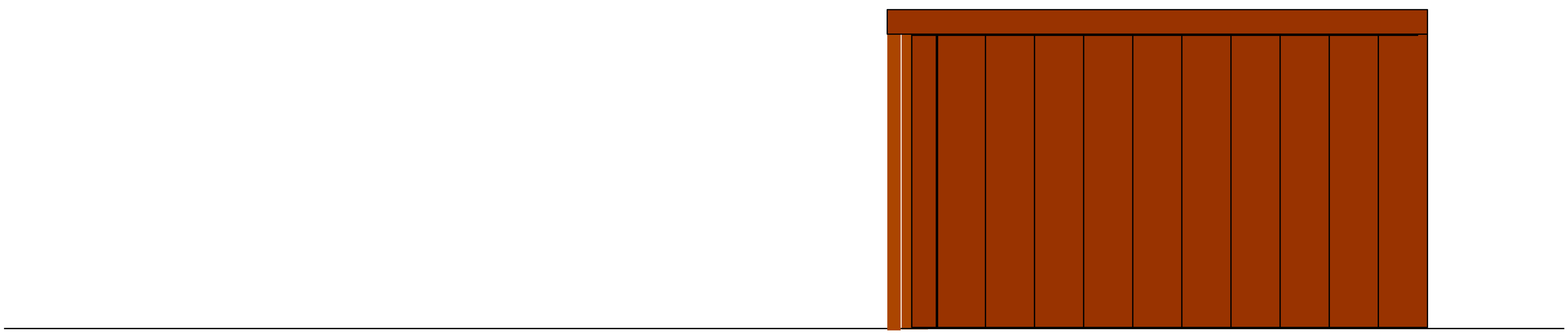
- Example: Park-a-lot 2000: An automated car parking system
  - One thread steers the car
  - Another thread steers the garage door opener
- ***Coordination how?***



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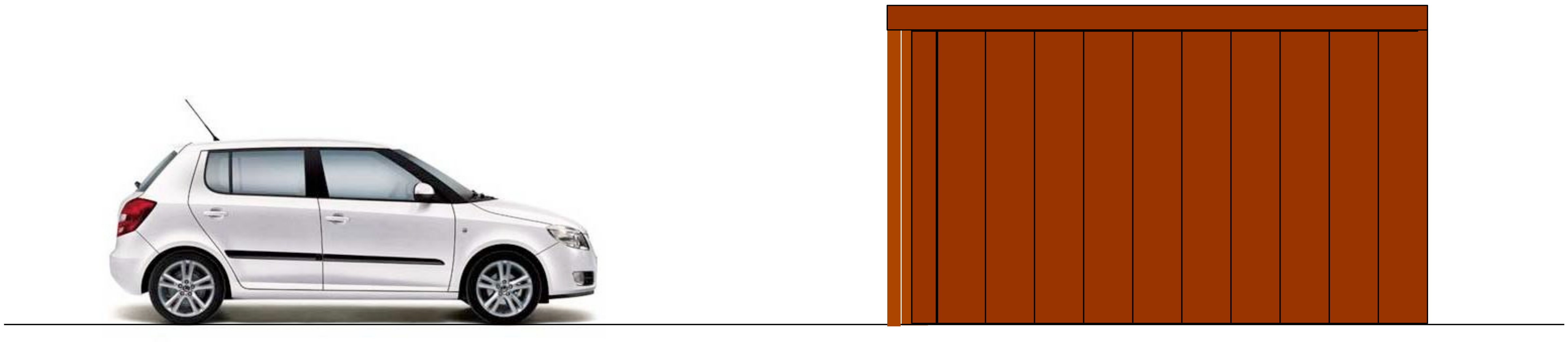

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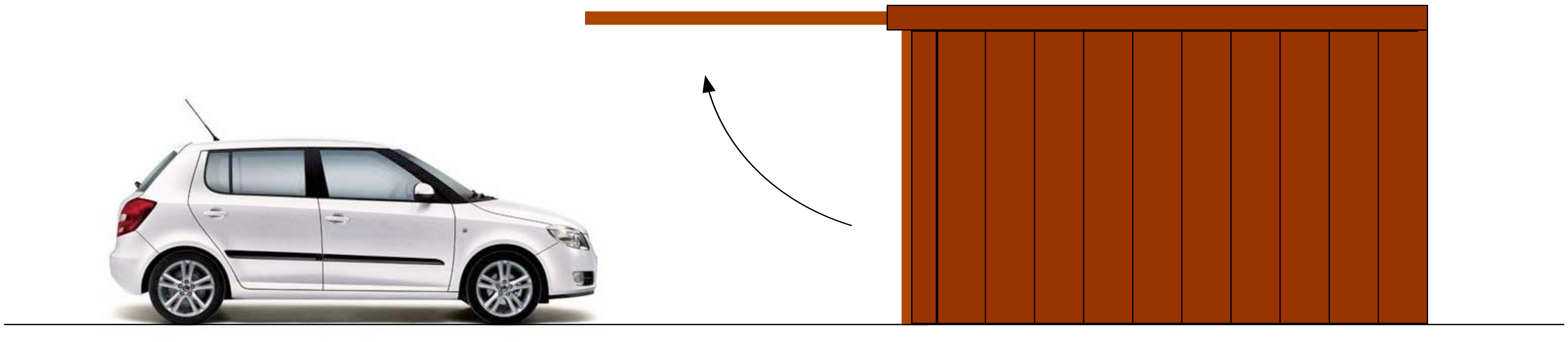

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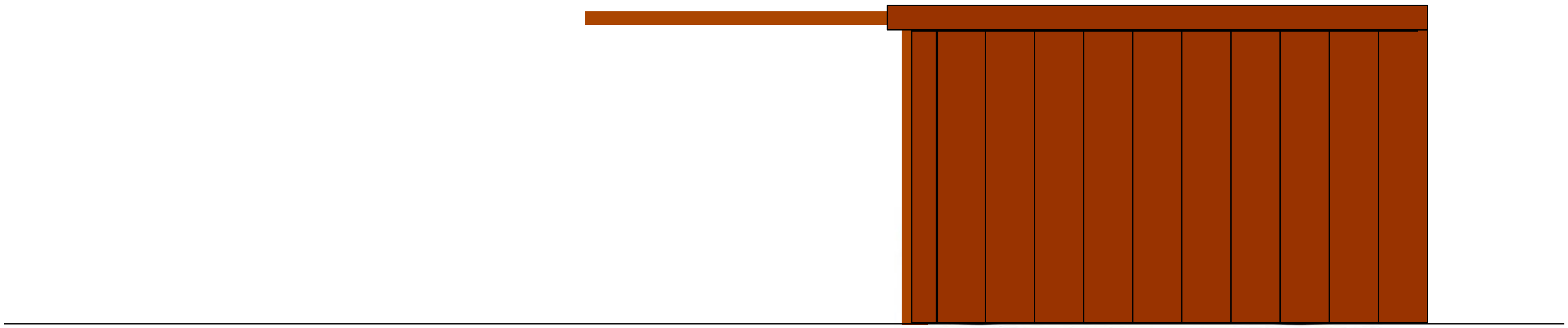

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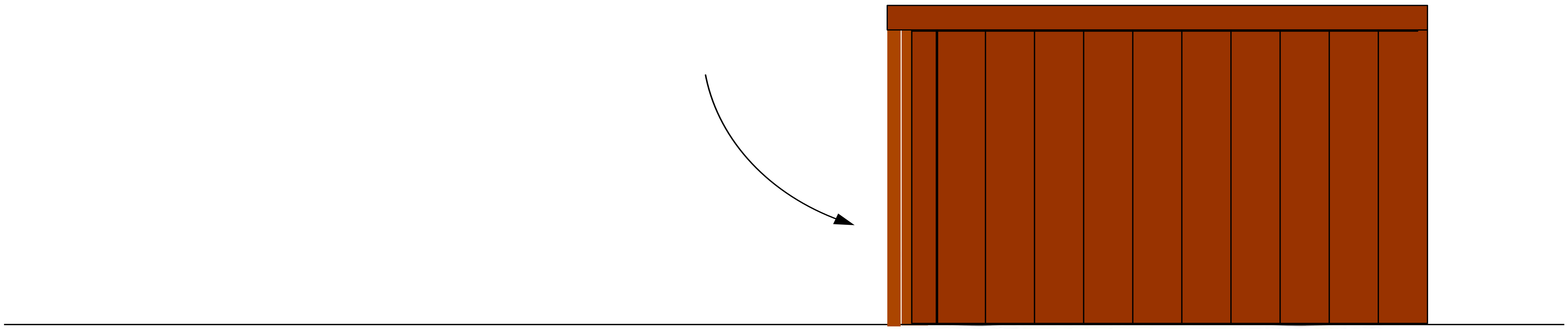

Signalling mechanism - Which?

- We need Conditionals... But How?
  - Fundamental point is that we have a
    - Receiver/Waiter who waits on a conditional variable
    - Sender/Indicator who signals this particular conditional variable at some point

Conditionals - How do you code it?

```
Mutex m;
Conditional c;
```

```
void theWaiter()
{
   lock(m);

   while (!what_we_are_waiting_for)
   {
       condWait(c, m);
   }

   unlock(m);
}
```

```
void theIndicator()
{
  lock(m);
  // Do something...
  what_we_are_waiting_for = true;
  // unlock(m) here - is also okay
  condSignal(c);
  unlock(m);
}
```

How you understand conditionals... - Receiver/Waiter

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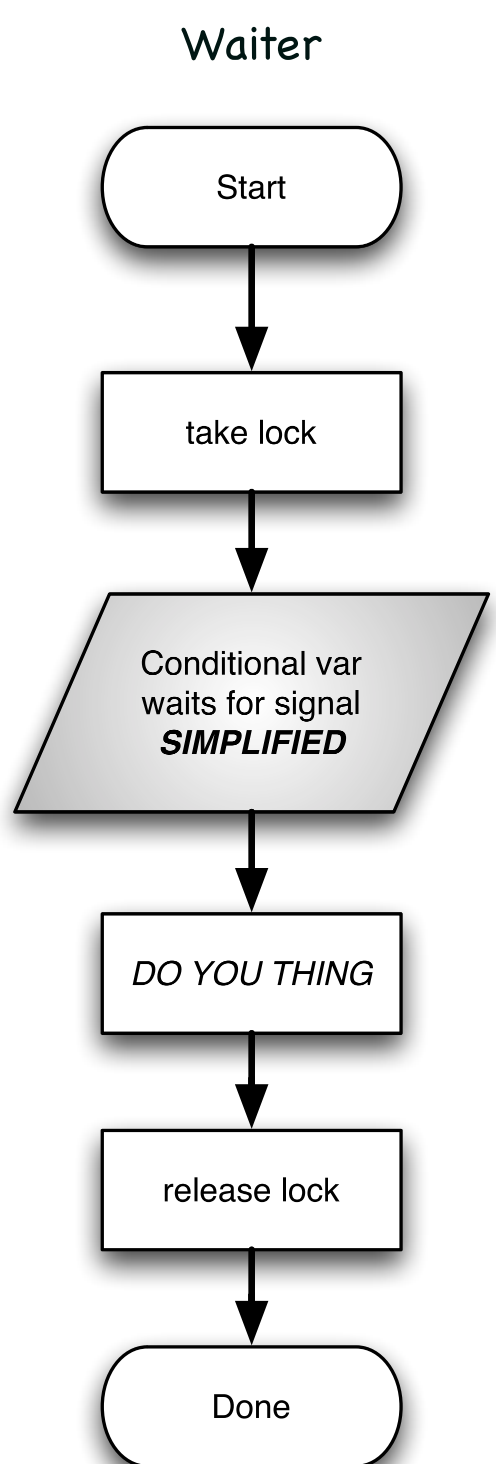

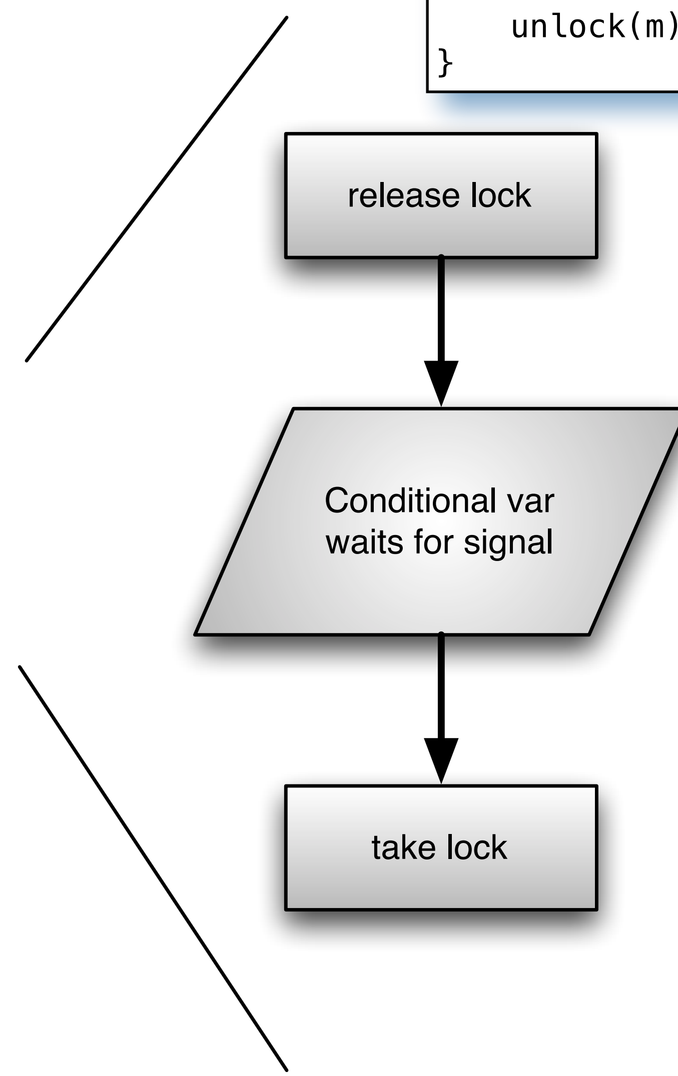

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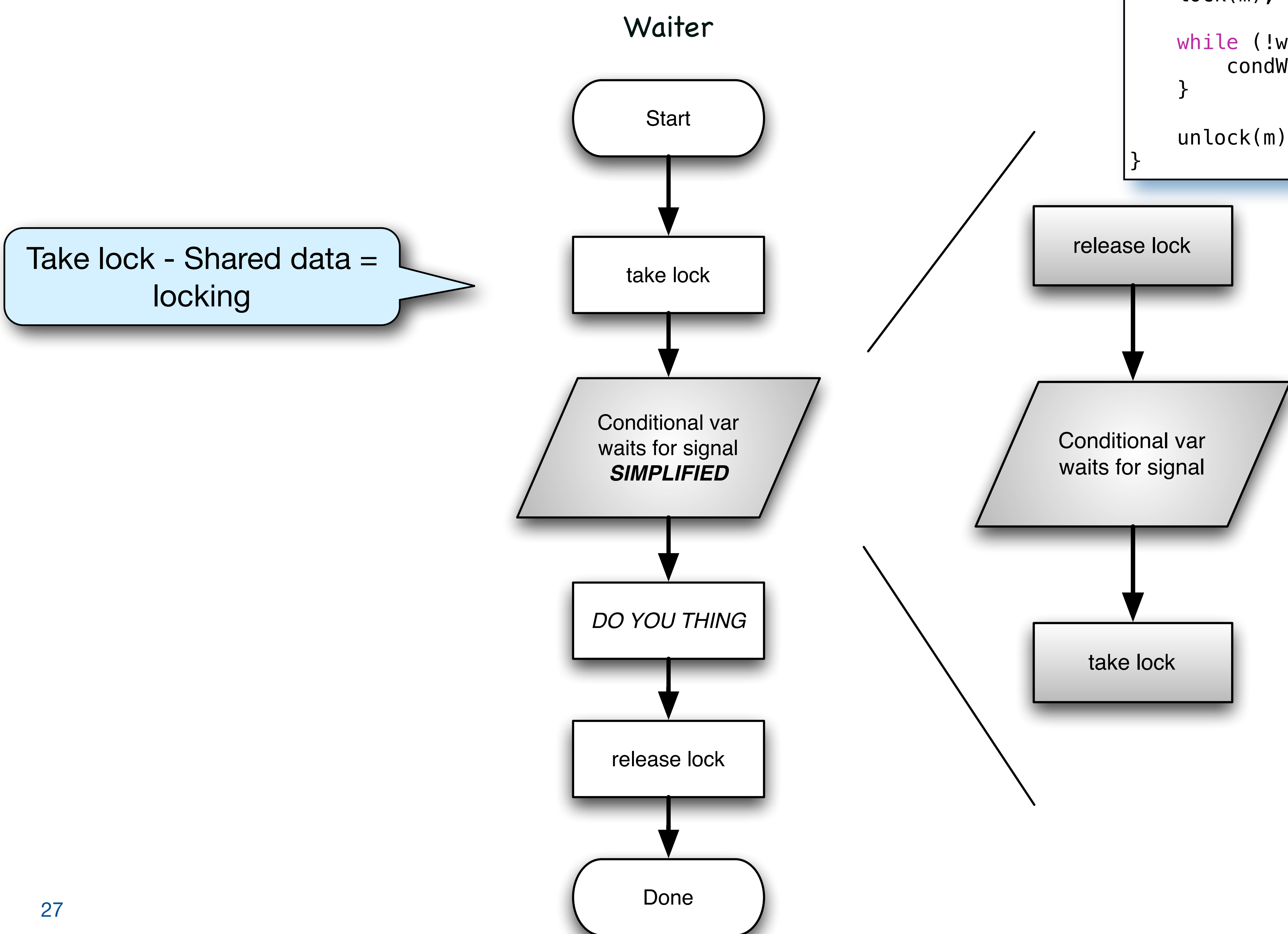

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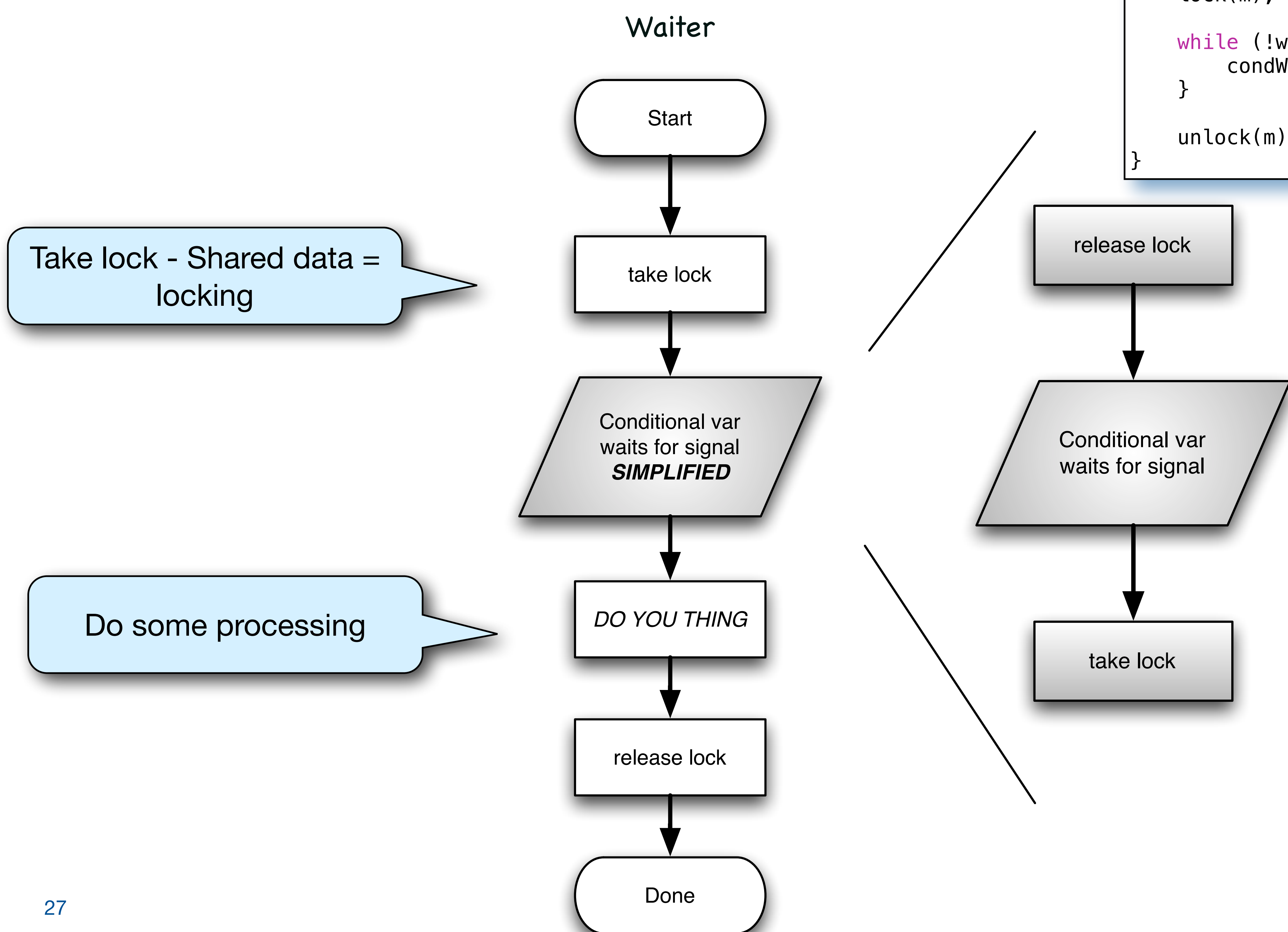

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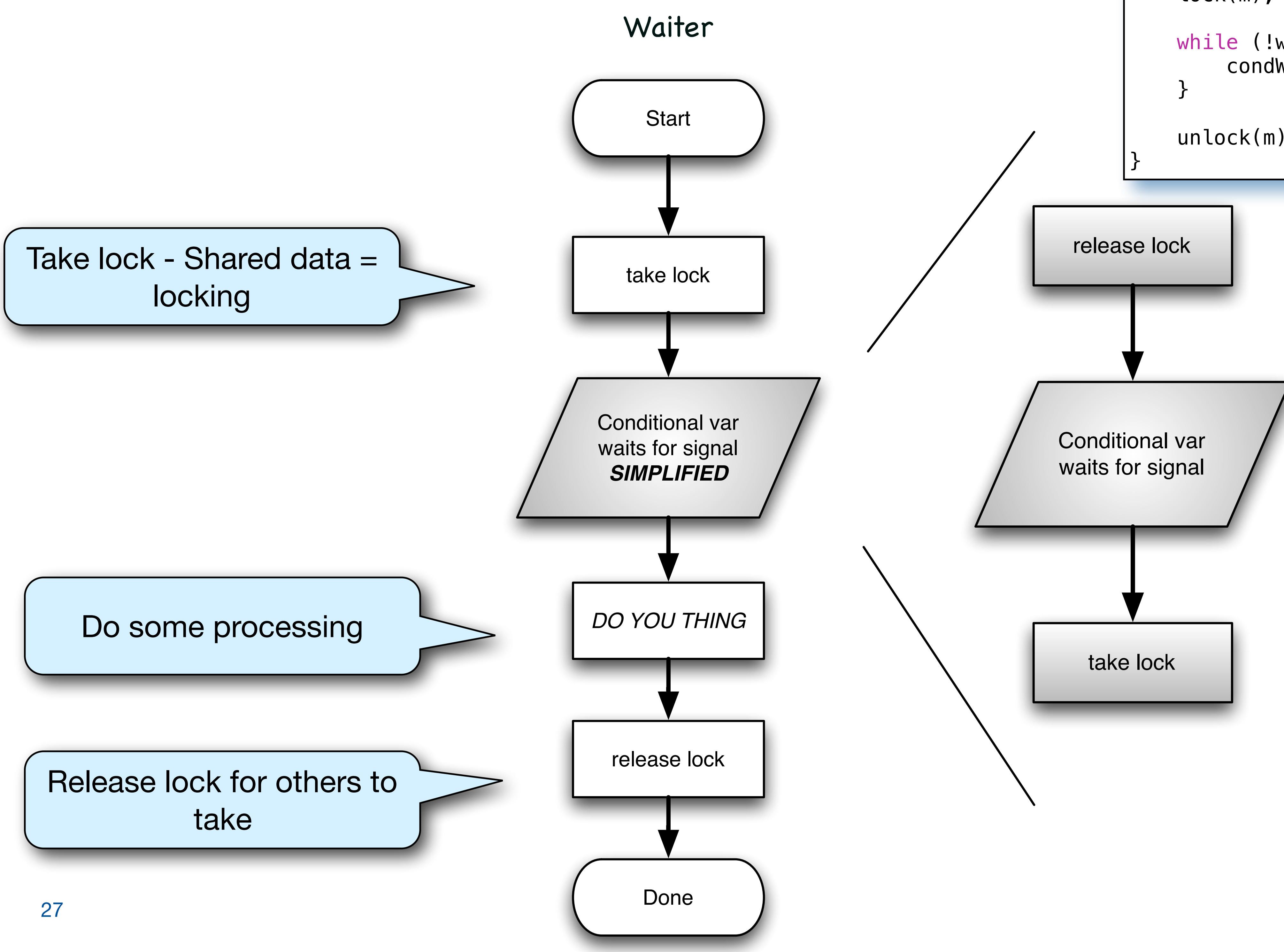

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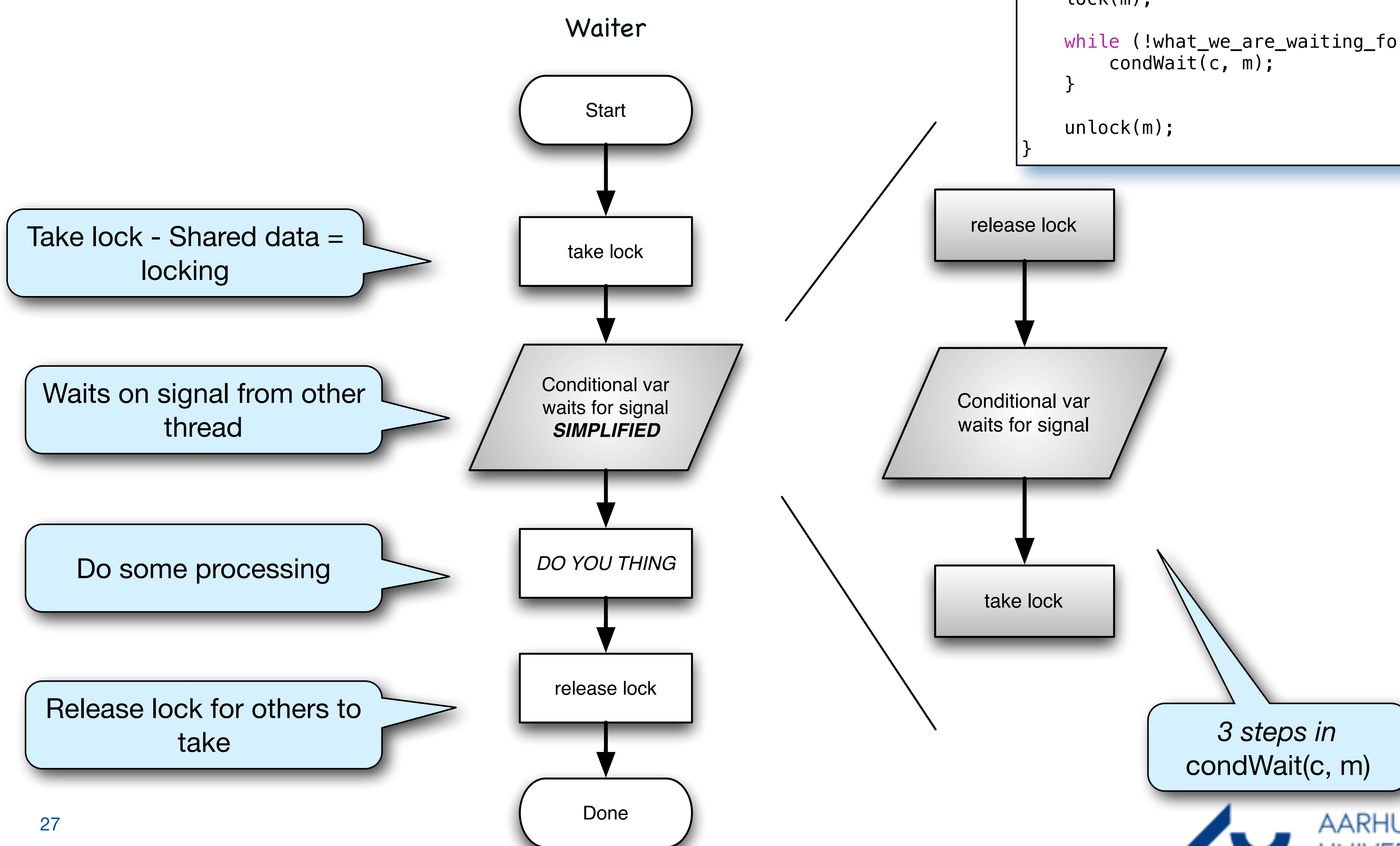

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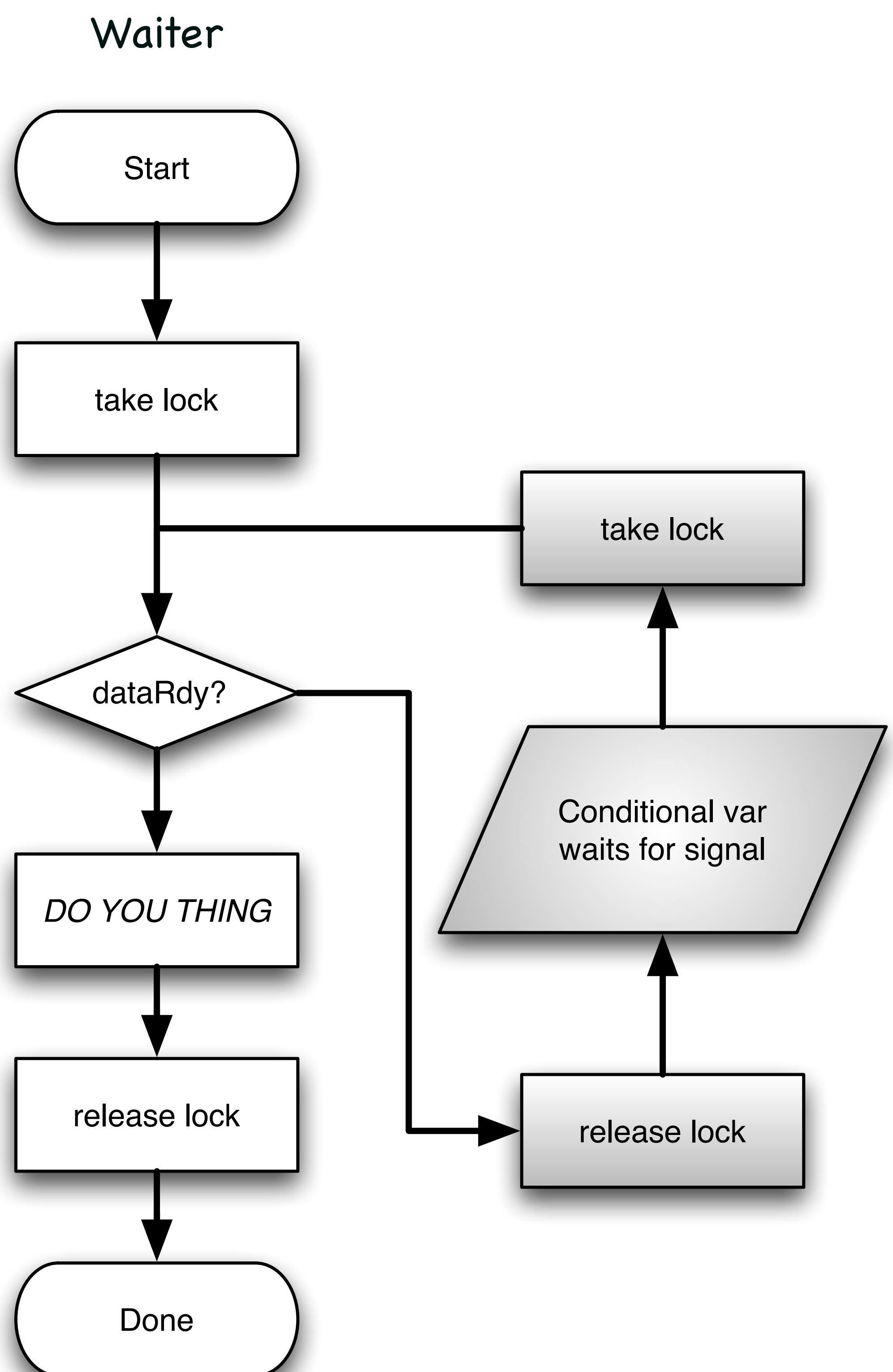

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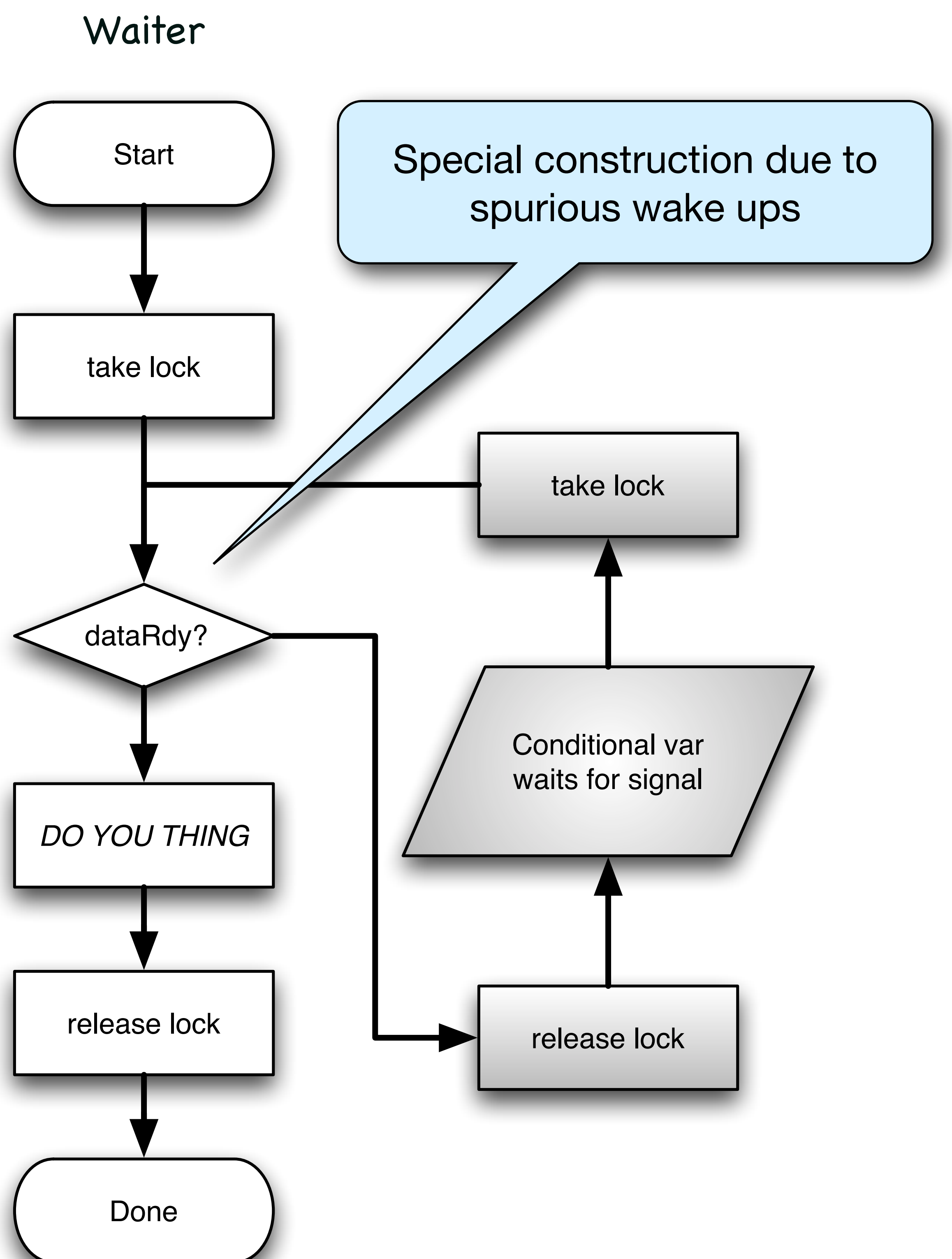

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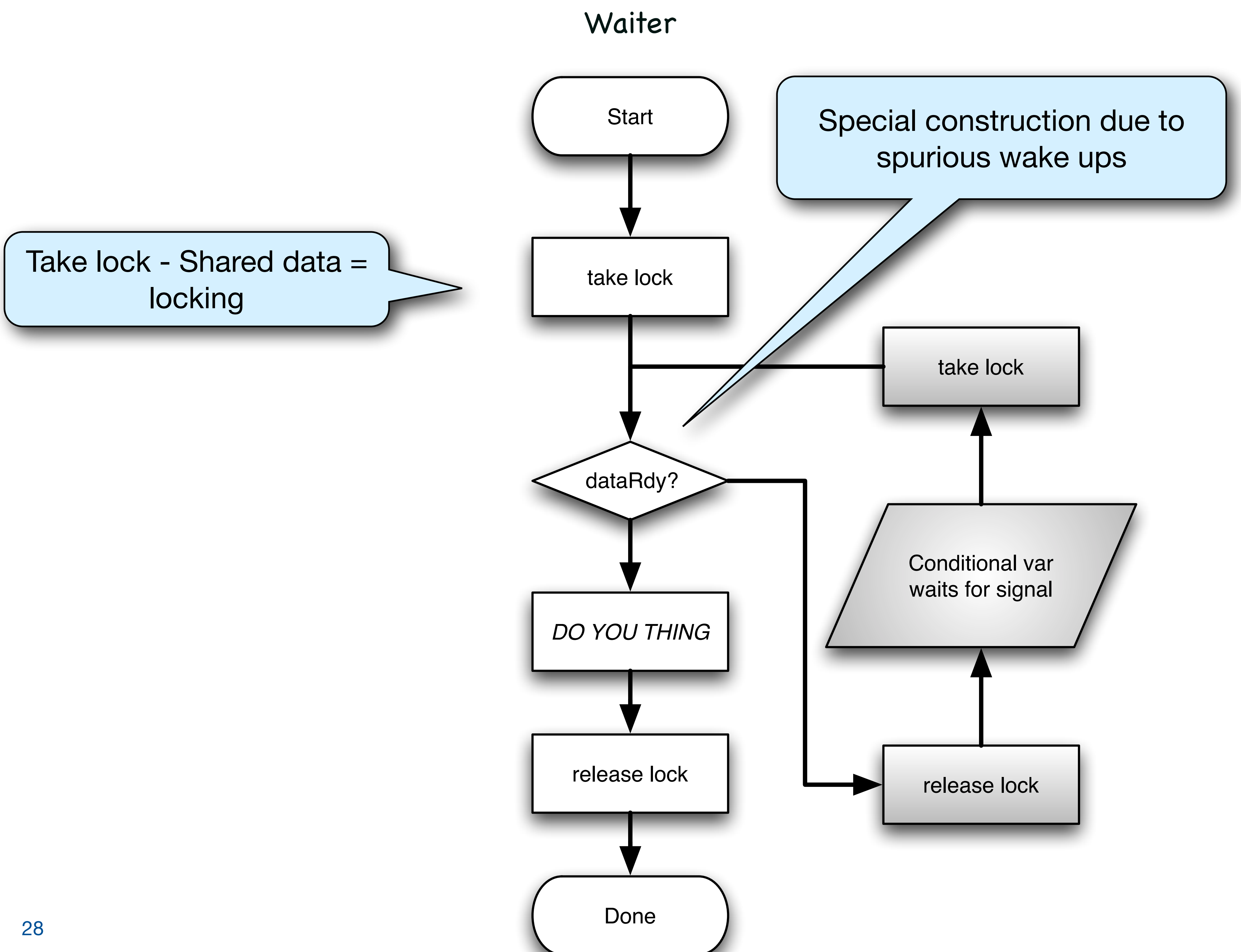

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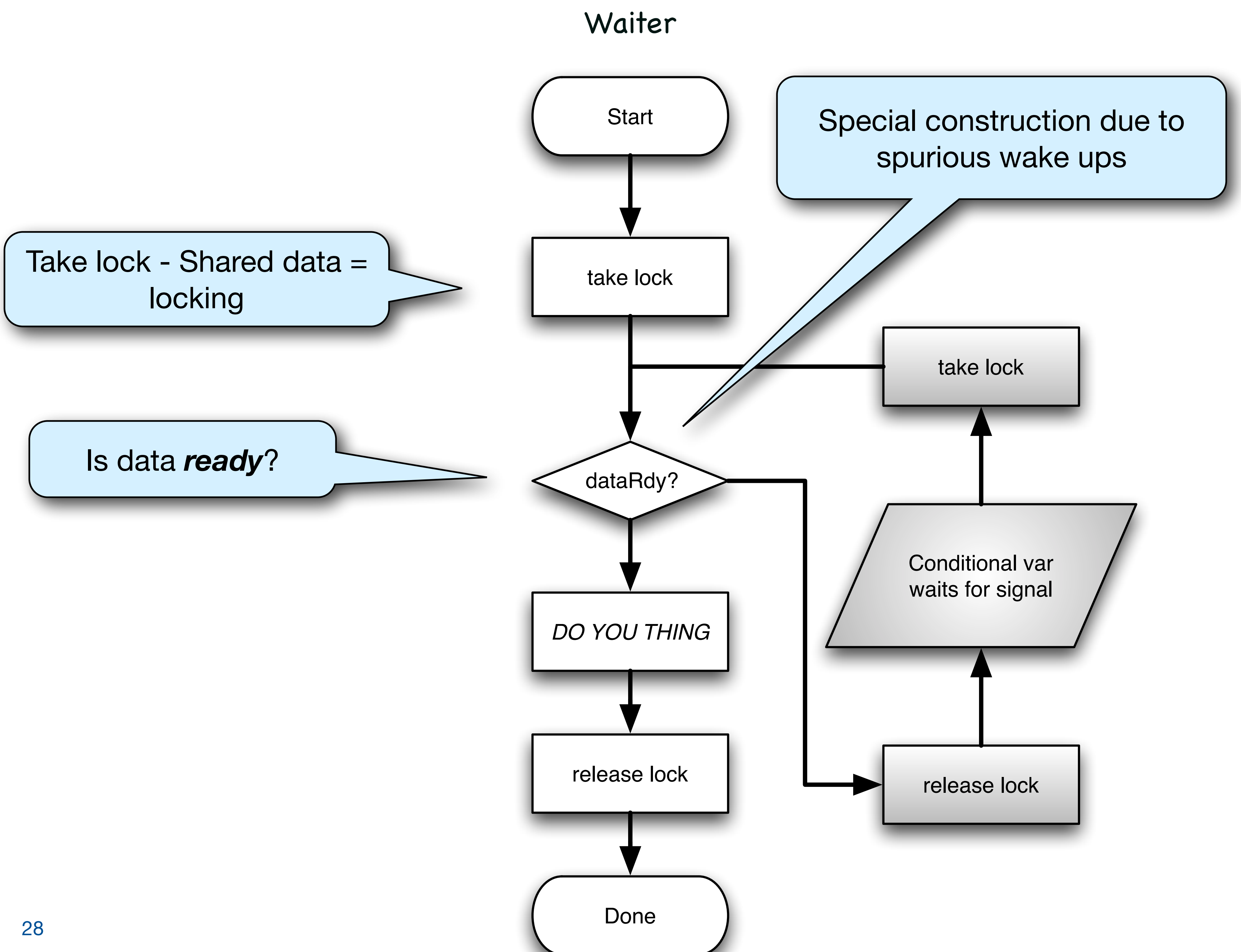

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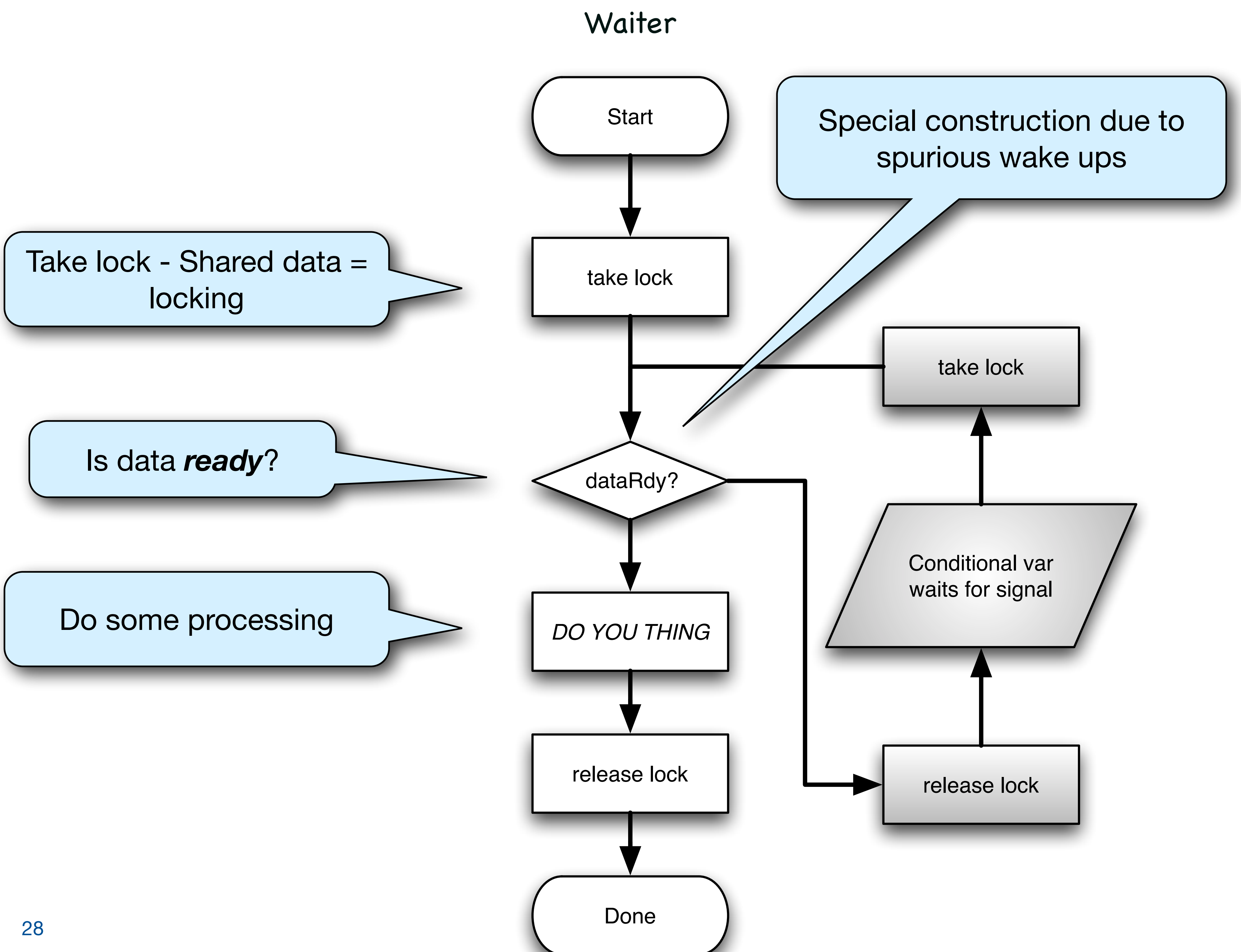

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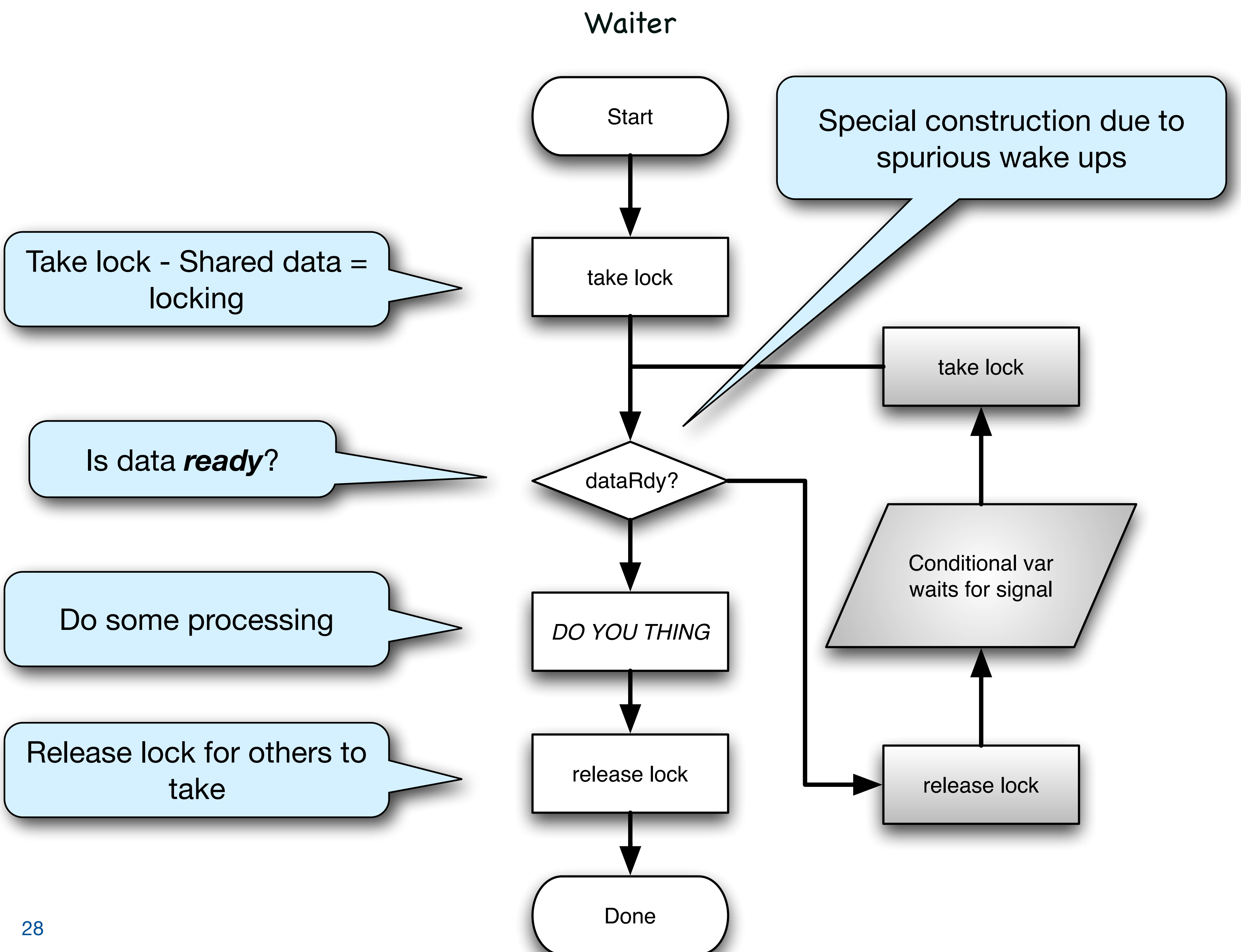

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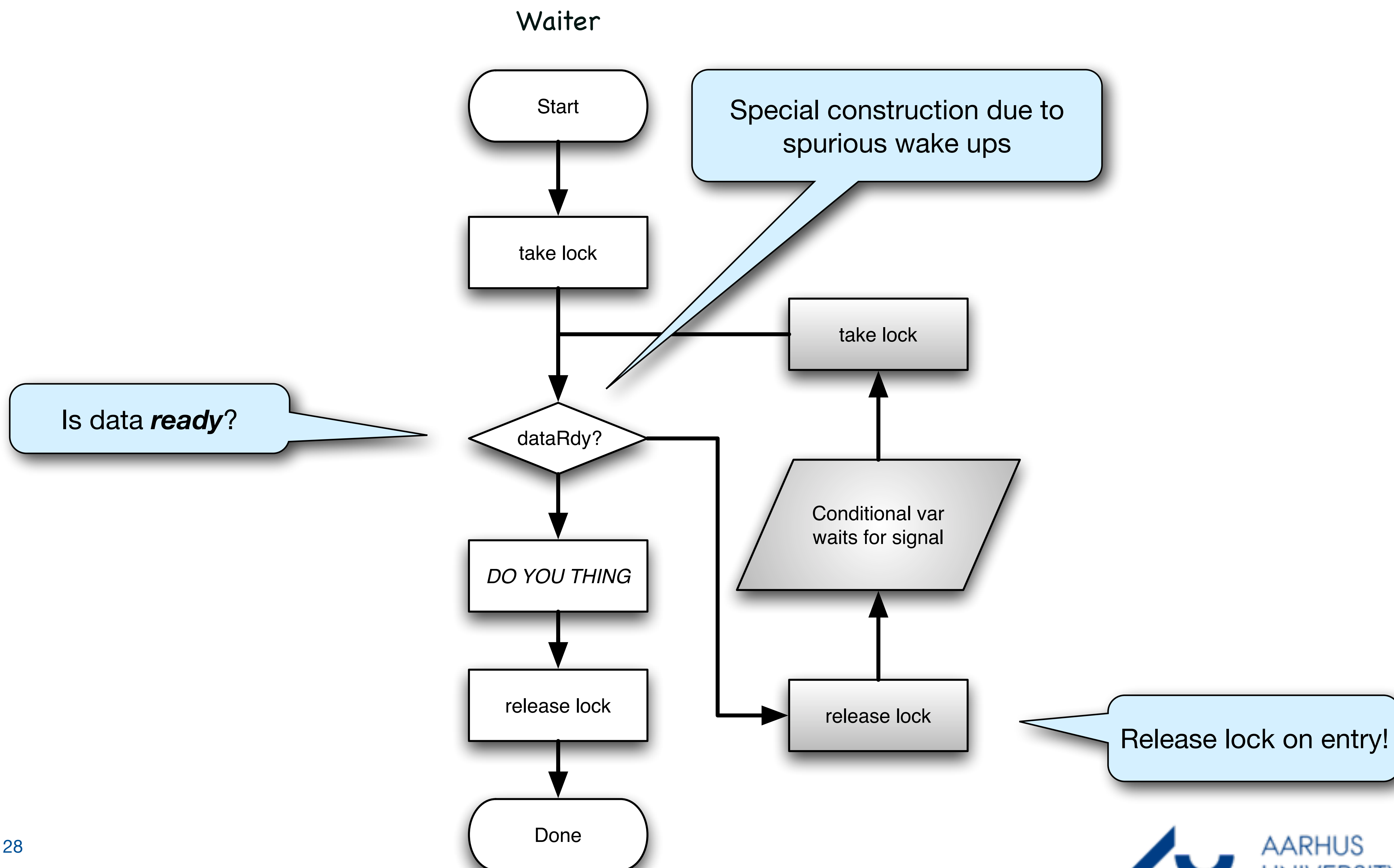

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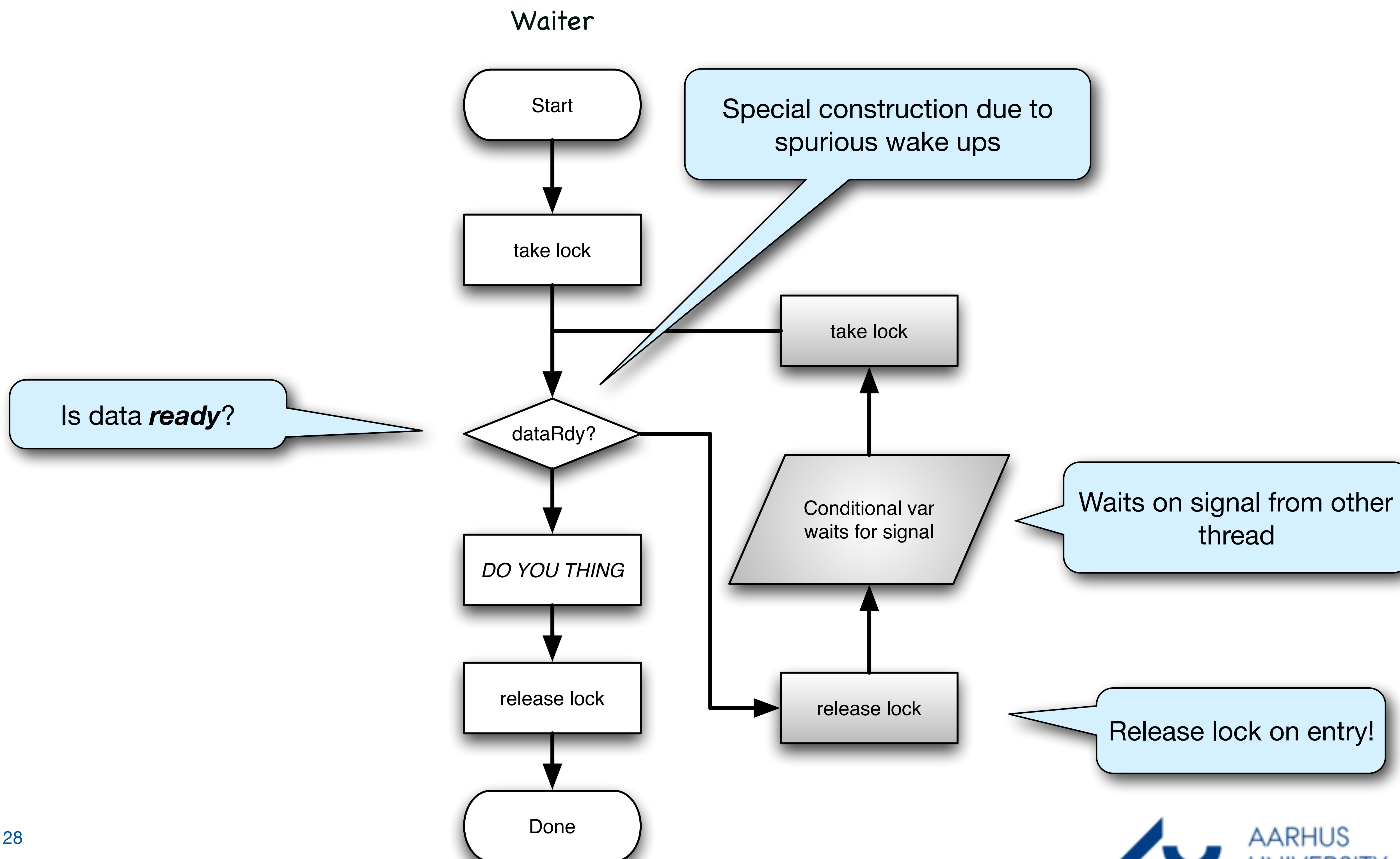

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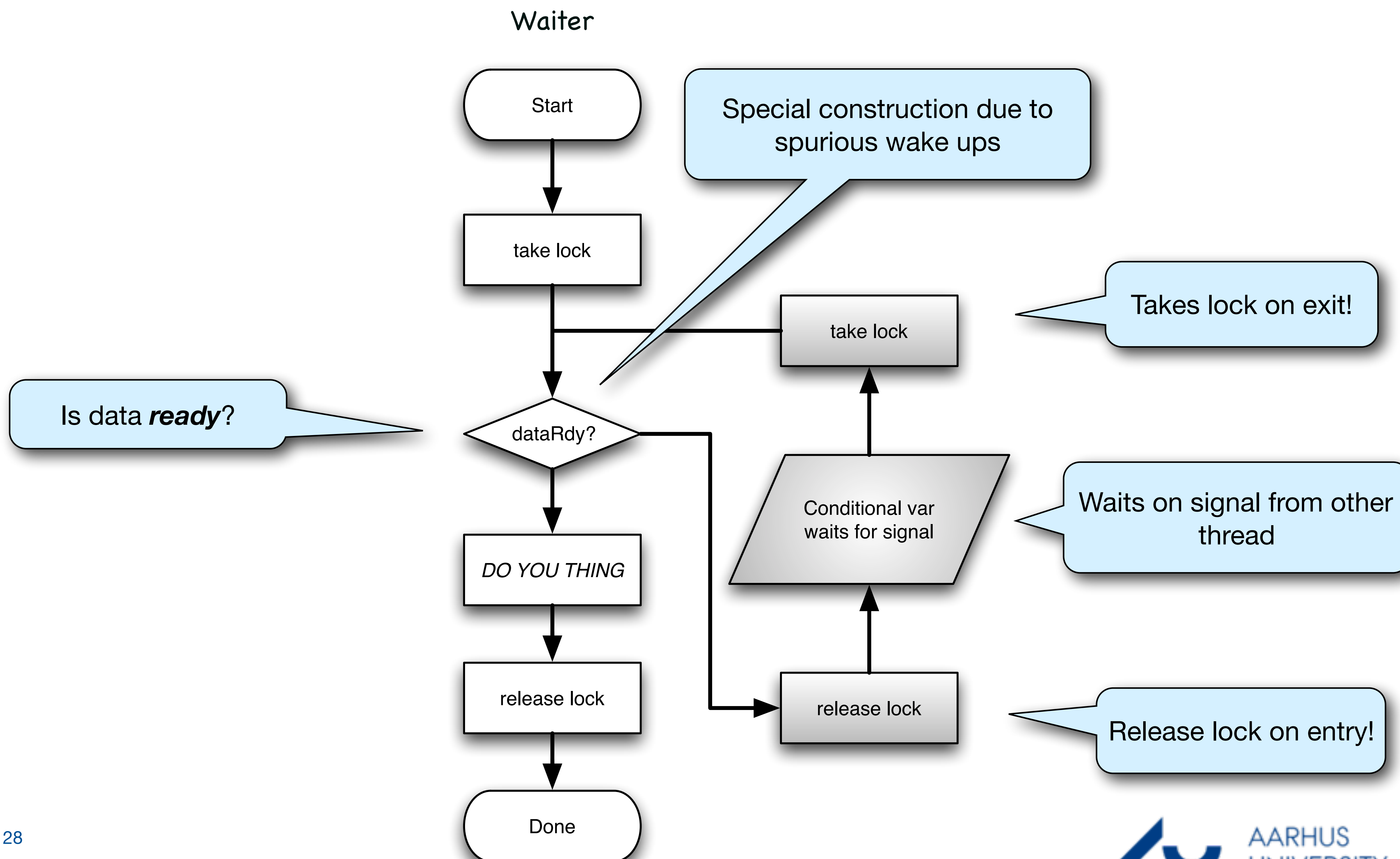

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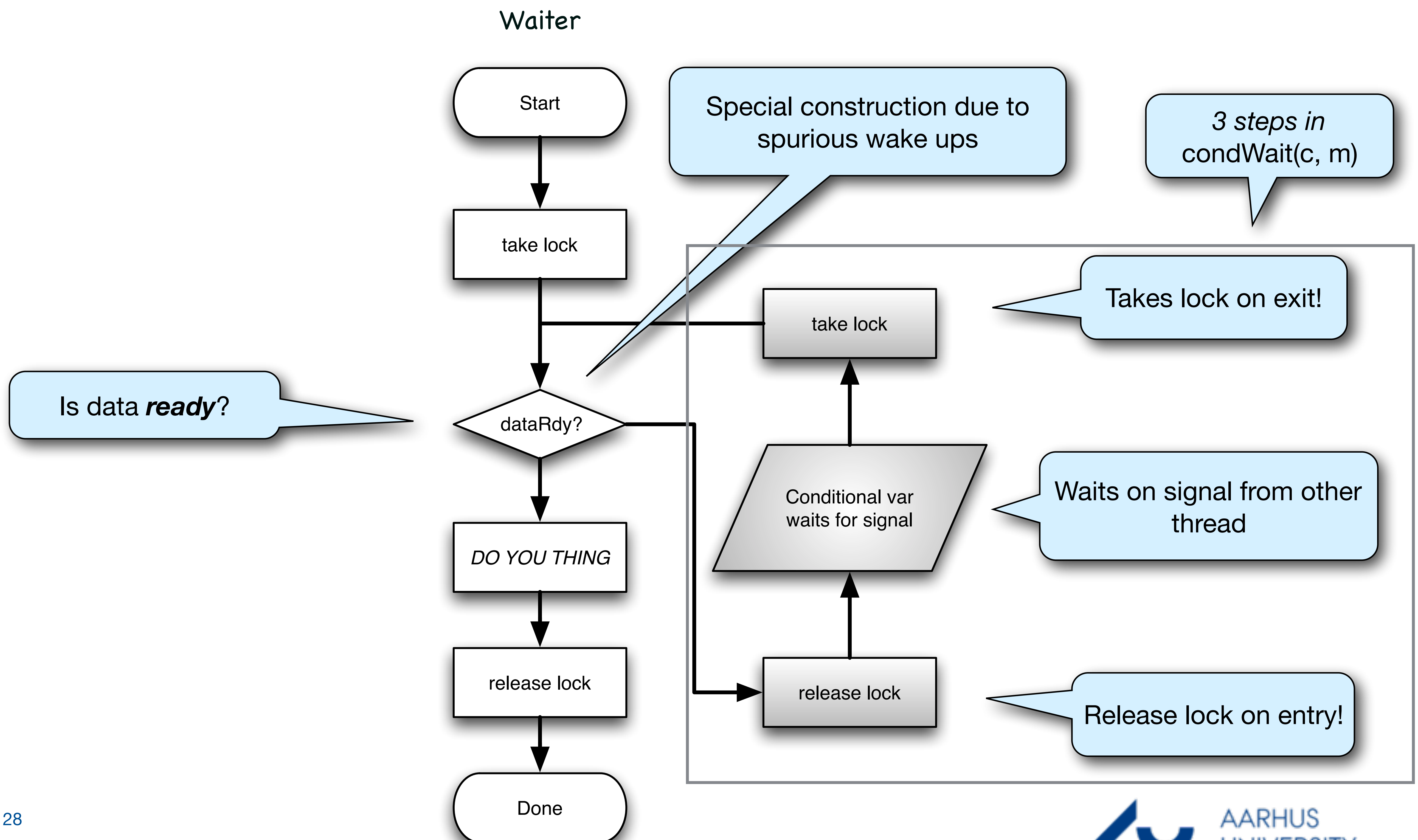
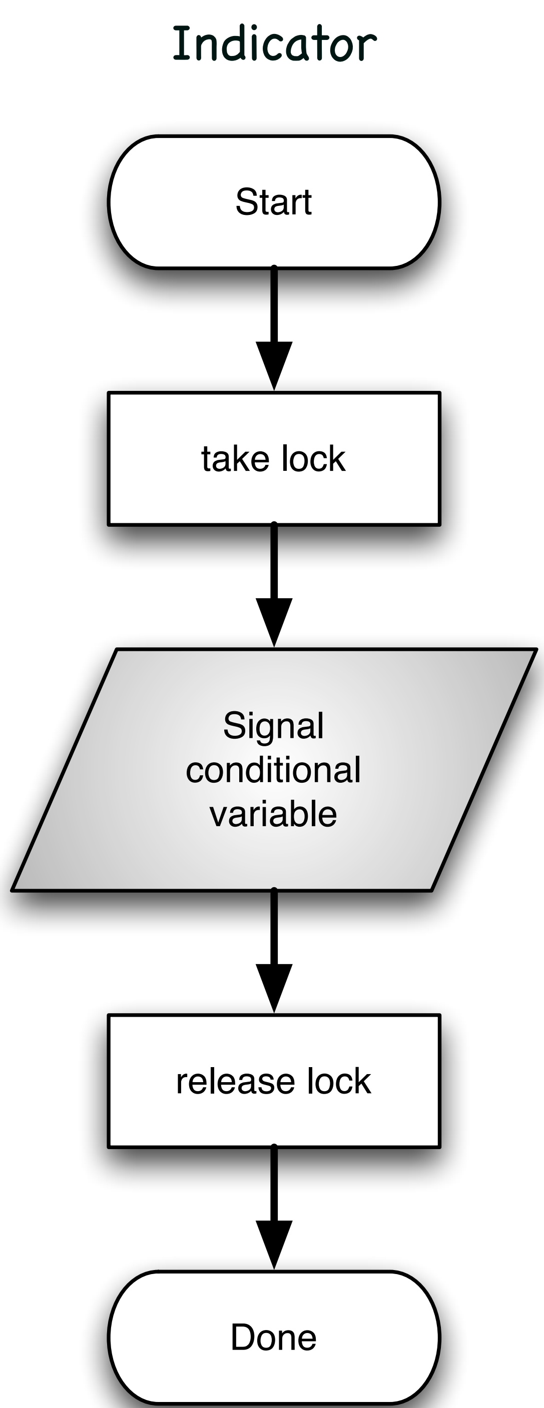


We need Conditionals... - Sender/Indicator

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void theIndicator()
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   lock(m);
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   condSignal(c);
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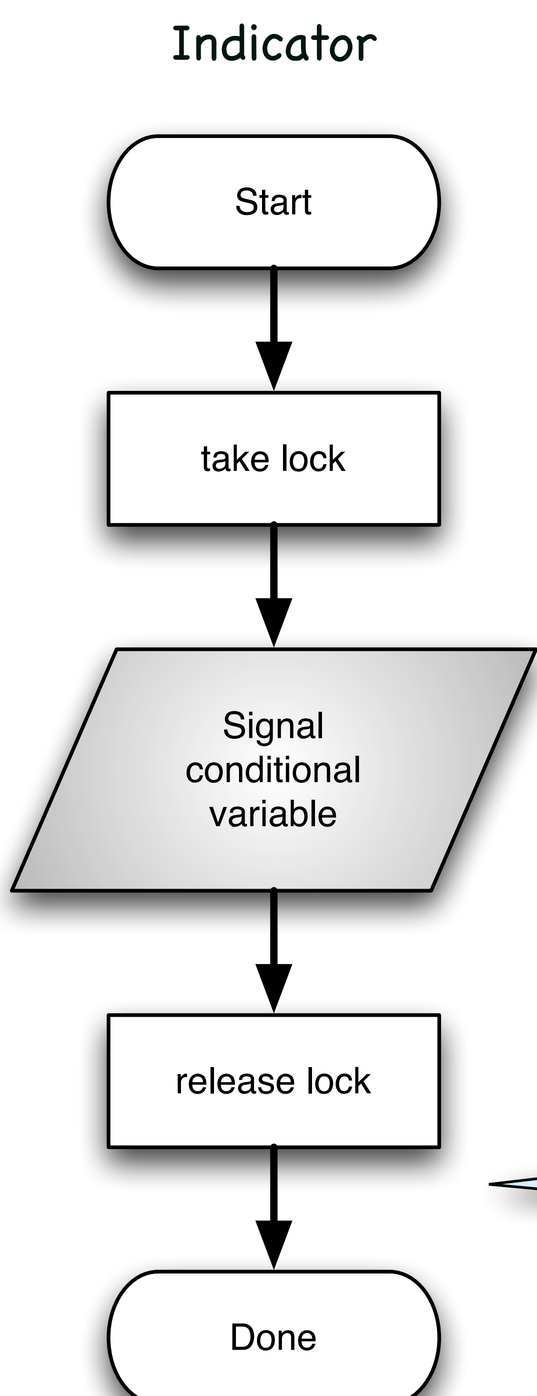

When some common data has been updated -> The conditional variable is signaled

Does ***NOT*** need to be protected. ***WHY?***

Park-a-lot 2000 - Feeble attempt

- Our first attempt:

Park-a-lot 2000 - Feeble attempt

- Our first attempt:

```
carDriverThread()
{
   driveUpToGarageDoor()
   sleep(GARAGE_DOOR_OPEN_TIME);
   // Let's hope the door is open!
   driveIntoGarage();
}
```

```
garageDoorControllerThread()
{
   openGarageDoor()
   sleep(CAR_ENTER_GARAGE_TIME);
   // Let's hope the car is in!
   closeGarageDoor();
}
```

Park-a-lot 2000 - Feeble attempt

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   closeGarageDoor();
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```

- We need to be sure that…
  - The door is open before we move the car (car sync with garage door)
  - The car is in before we close the door (garage door sync with car)

Park-a-lot 2000

- Our second attempt: Two-way synchronization

Park-a-lot 2000

- Our second attempt: Two-way synchronization

```
carDriverThread()
{
   driveUpToGarageDoor();
   lock(mut);
   carWaiting = true;
   condSignal(entry);
   while(!garageDoorOpen)
     condWait(entry, mut);
   driveIntoGarage();
   carWaiting = false;
   condSignal(entry);
   unlock(mut);
}
```

```
garageDoorControllerThread()
{
   lock(mut);
   while(!carWaiting)
     condWait(entry, mut);
   openGarageDoor();
   garageDoorOpen = true;
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   while(carWaiting)
     condWait(entry, mut);
   closeGarageDoor();
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}
```

Park-a-lot 2000

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Park-a-lot 2000

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- This works!
  - 2-way synchronization
  - All waits are matched with signals

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Types of synchronization methods

Types of synchronization methods

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- Generally, there are three different types of semaphores for three different purposes:

  - Mutex: s=0 or s=1, belongs to one thread at a time
  - Conditionals Signaling facility used with a mutex
  - *Read/writable locks* *Multiple readers - Exclusive writer*

  - Counting semaphore: $s \geq 0$, shared among threads
  - Binary semaphore: s=0 or s=1, shared among threads

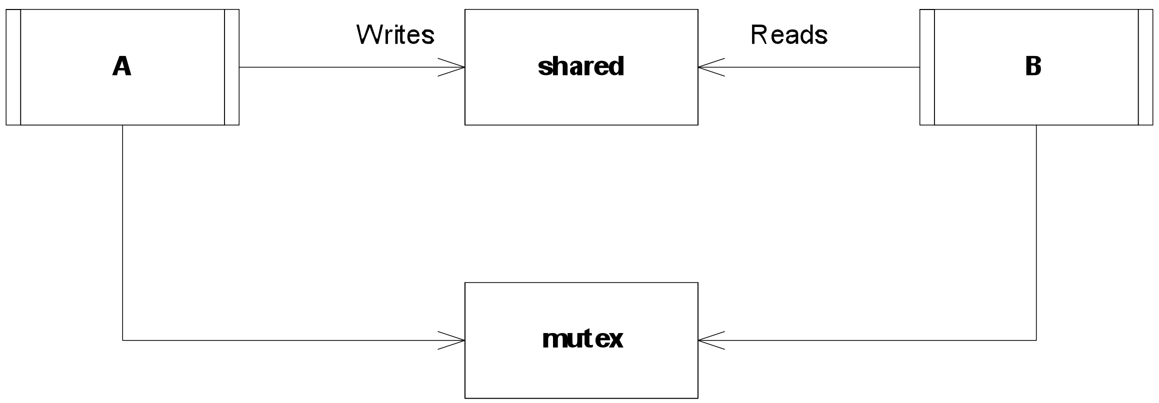
POSIX Synchronization mechanisms (Not all included)

```
#include<pthread.h>

int pthread_mutex_init(pthread_mutex_t* mutex, pthread_mutex_attr_t *mutexattr);
int pthread_mutex_lock(pthread_mutex_t* mutex);
int pthread_mutex_unlock(pthread_mutex_t* mutex);
int pthread_mutex_destroy(pthread_mutex_t* mutex);

int pthread_rwlock_init(pthread_rwlock_t* mutex, pthread_rwlockattr_t *mutexattr);
int pthread_rwlock_rdlock(pthread_rwlock_t* mutex);
int pthread_rwlock_wrlock(pthread_rwlock_t* mutex);
int pthread_rwlock_unlock(pthread_rwlock_t* mutex);
int pthread_rwlock_destroy(pthread_rwlock_t* mutex);

int pthread_cond_init(pthread_cond_t *cond, const pthread_condattr_t *attr);
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
int pthread_cond_destroy(pthread_cond_t *cond)
```

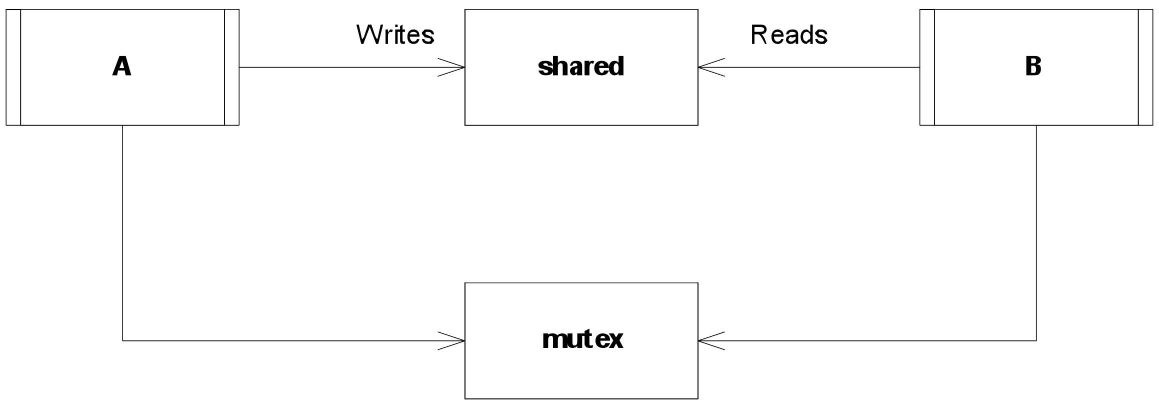
```
#include<semaphore.h>

int sem_init(sem_t* sem,          // Semaphore ID
        int pshared,          // Unsupported. Set to 0
        unsigned int value    // Initial value , >=0
        );

int sem_destroy(   sem_t* sem);   // Semaphore ID to destroy
int sem_wait(sem_t* sem);         // Wait for sem
int sem_post(sem_t* sem);         // Post (signal) sem
```

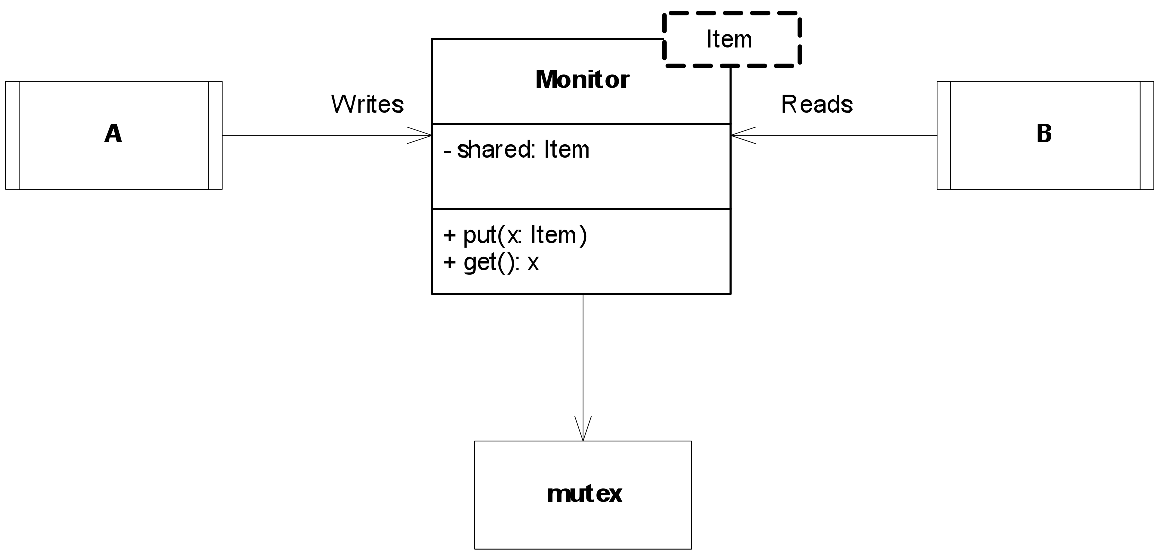
Aids / Tools

The Monitor

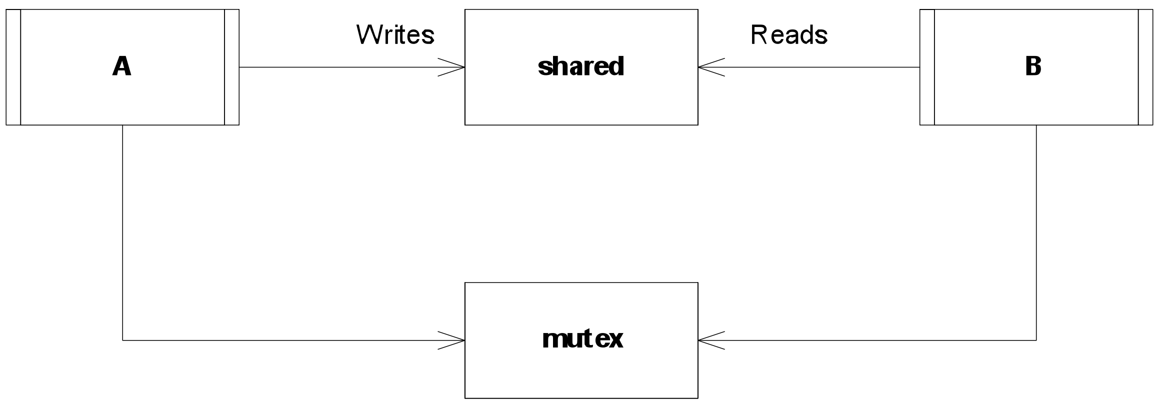


The Monitor

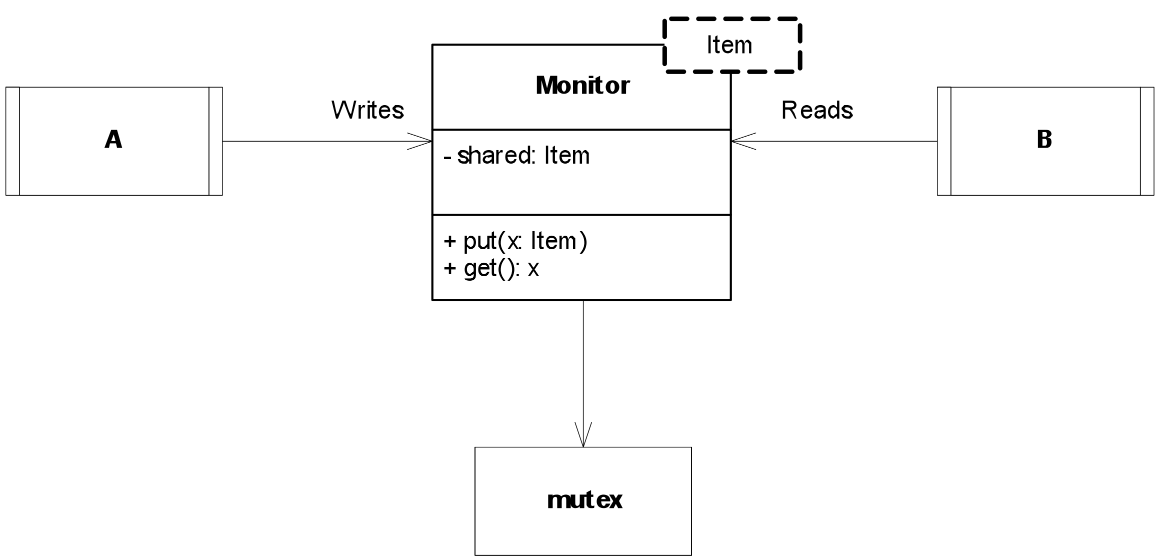

A
Writes
shared
Reads
B
mutex


Item
Monitor
A
Writes
Reads
B
- shared: Item
+ put(x: Item)
+ get(): x
mutex

The Monitor



- Monitor: A template class
  - When accessed, the Monitor
    1. takes mutex,
    2. accesses shared,
    3. releases mutex
  - Responsibility for mutual exclusion: Programmer → monitor



- Any drawbacks/consequences?
  - Complete copy of shared returned – takes time
  - Exception between lock() and unlock()?

The Scoped Locking idiom

- A idiom pattern to ensure proper mutex clean-up, even on errors
- The idea: Create an object that automatically takes and releases a mutex at proper times – how?
  - lock() → constructor
  - unlock() → destructor
- ***How does this ensure clean-up?***
  - ***Generalized idiom called RAII - Learn IT!!!***

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