Concurrent Systems

Exercise 05 – Non-Blocking Synchronisation

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Agenda

Non-Blocking Data Structures

Lock-free Events

Worker Thread Notification

Assignment 5

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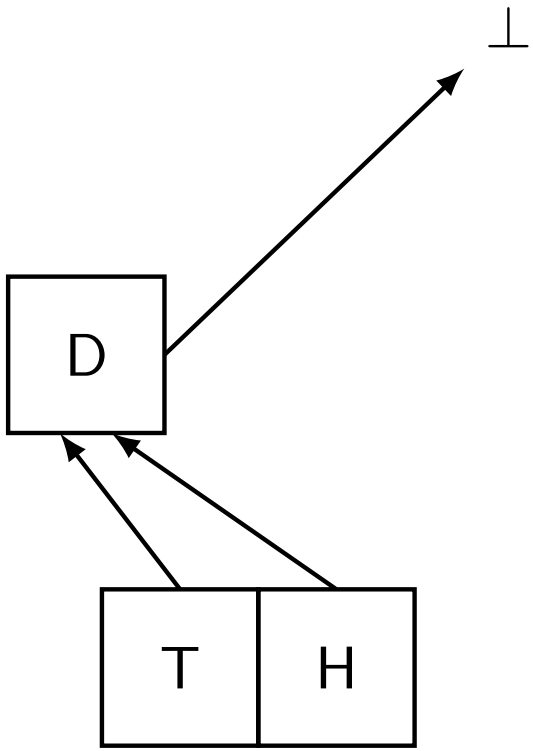
Non-blocking queues

- Many queue algorithms have been published
  - ... through scientific channels, e.g. [2, 3, 6]
  - ... through non-scientific channels, e.g. [4]
- Minimal interface
  - At least `enqueue()` and `dequeue()`
  - Sometimes `is_empty()`, `make_empty()`
- Differences between lock-free queue algorithms [5]
  - Single-producer $\leftrightarrow$ Multi-producer
  - Single-consumer $\leftrightarrow$ Multi-consumer
  - Lock-free $\leftrightarrow$ Wait-free
  - Nonintrusive $\leftrightarrow$ intrusive
  - Node-based ("Unbounded") $\leftrightarrow$ Array-based ("bounded") $\leftrightarrow$ Hybrid
  - Consistency guarantees
  - ...

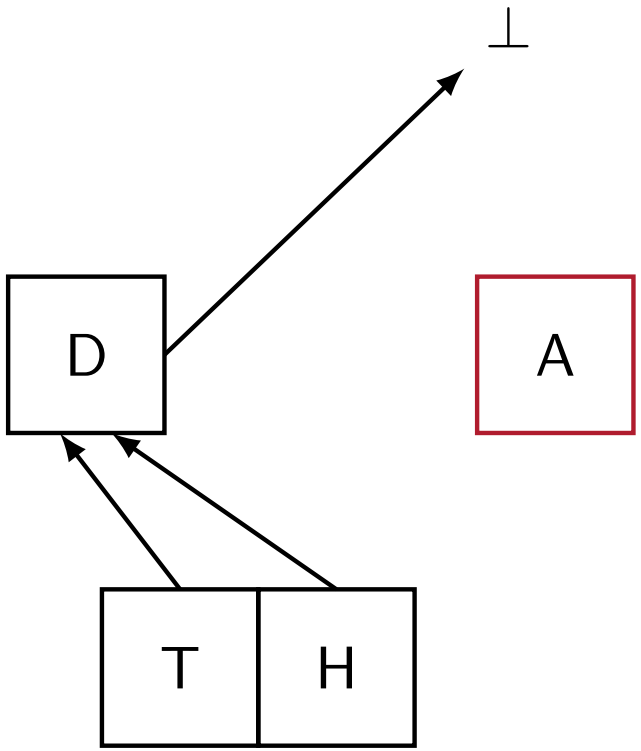
Queue example

- Source code is online:
  `http://www.1024cores.net/home/lock-free-algorithms/queues/intrusive-mpsc-node-based-queue`
- Multi-producer Single-consumer (MPSC)
- Wait-free
- Intrusive
- Node-based, unbounded
- Inconsistent: not always connected

Queue implementation



Queue implementation



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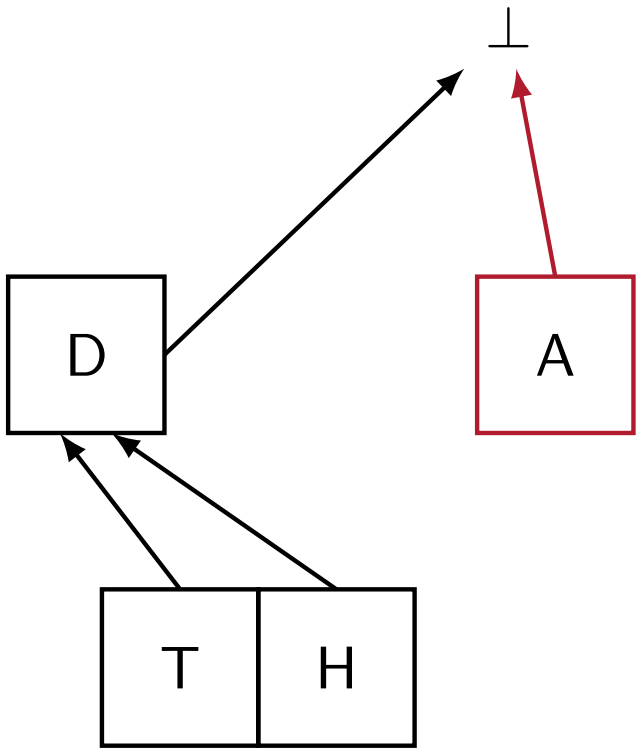

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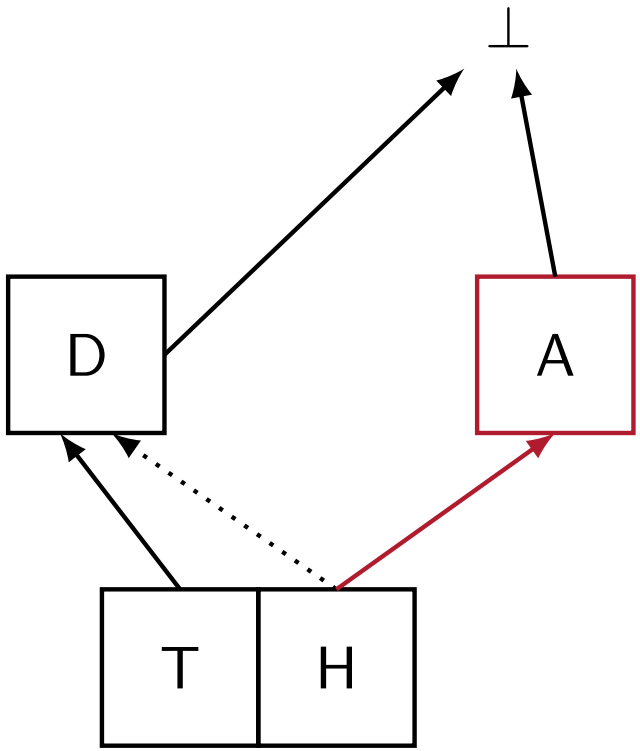

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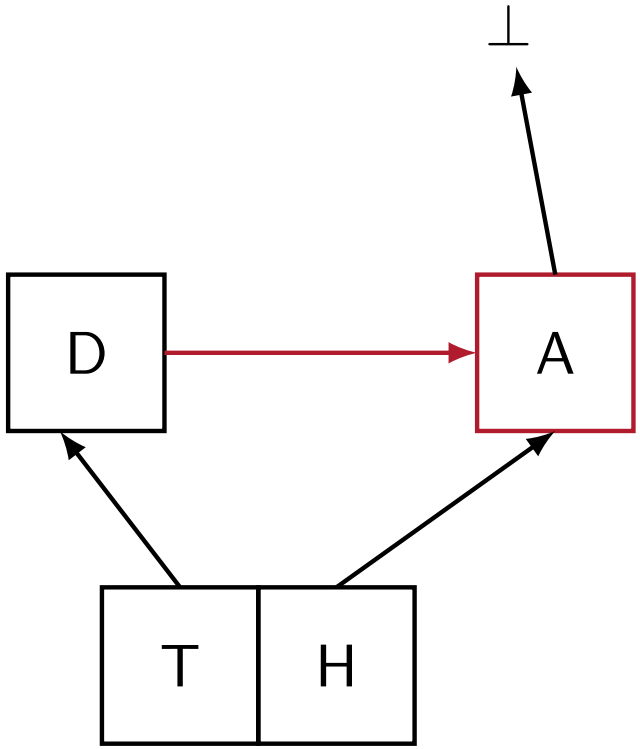

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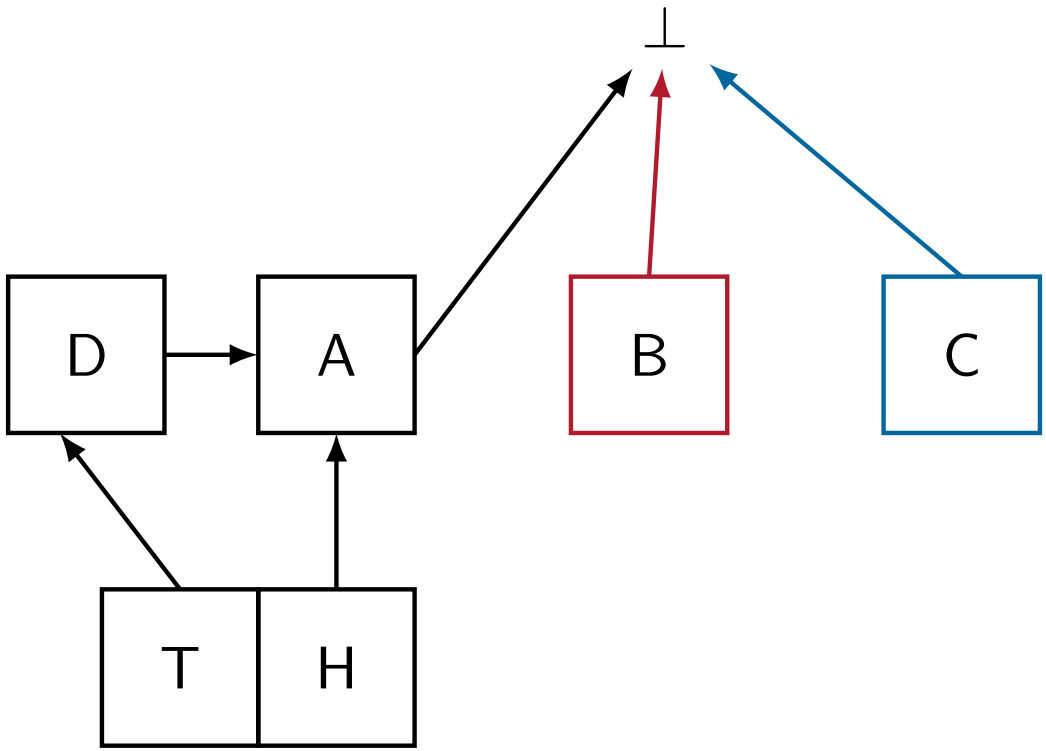

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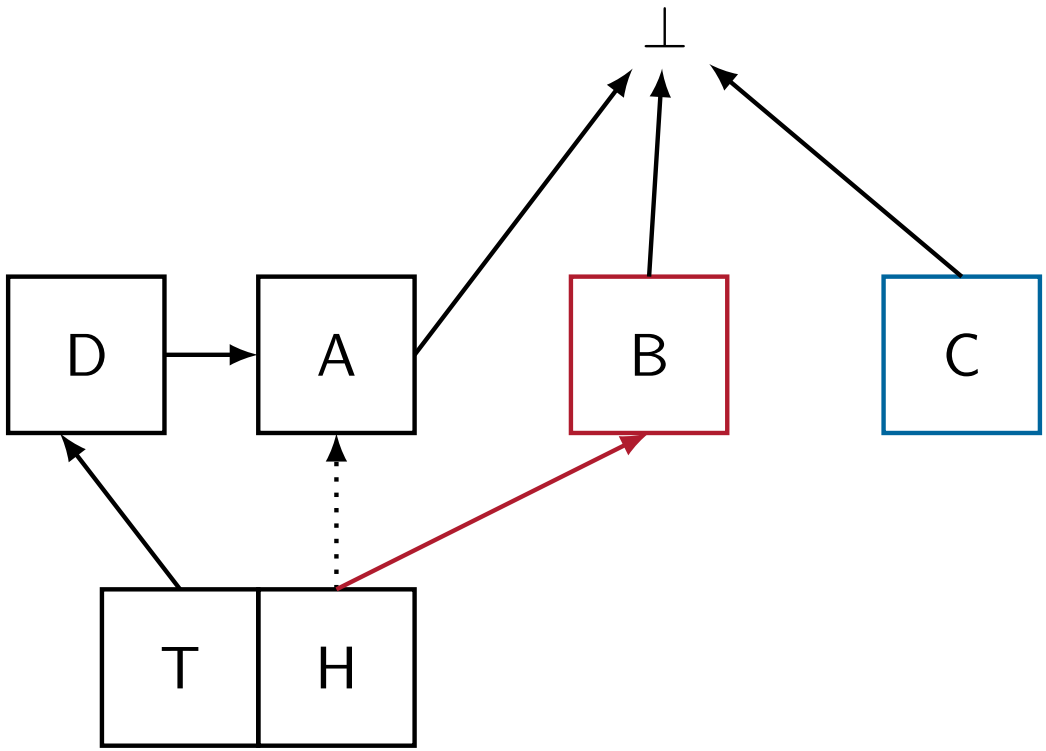
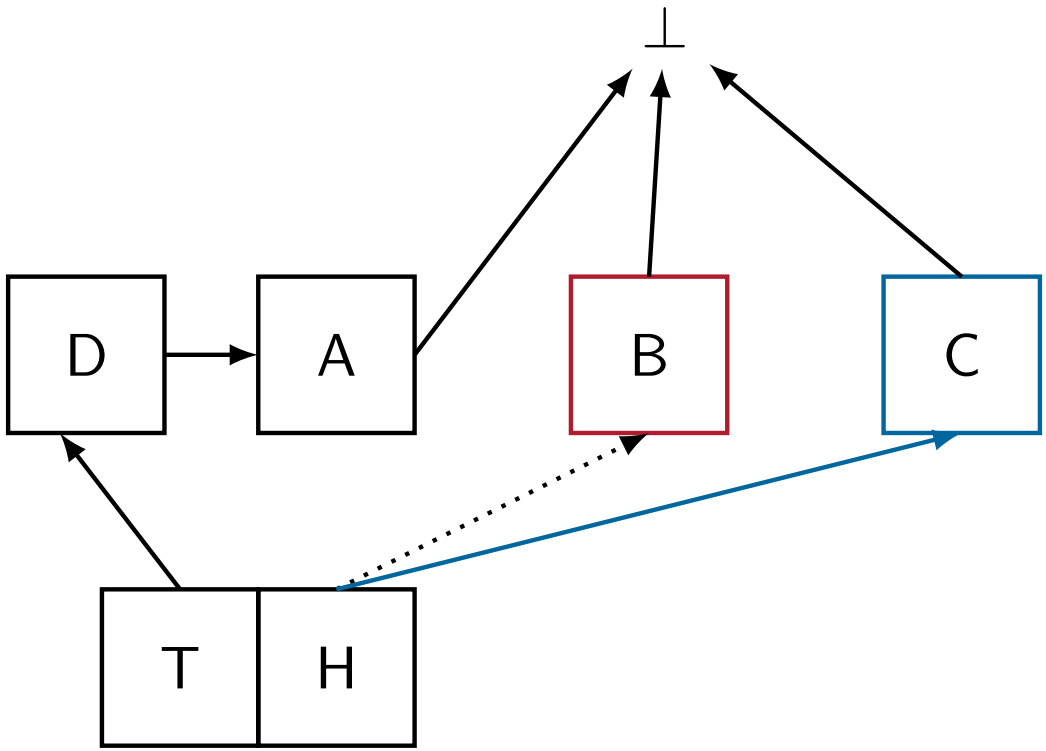
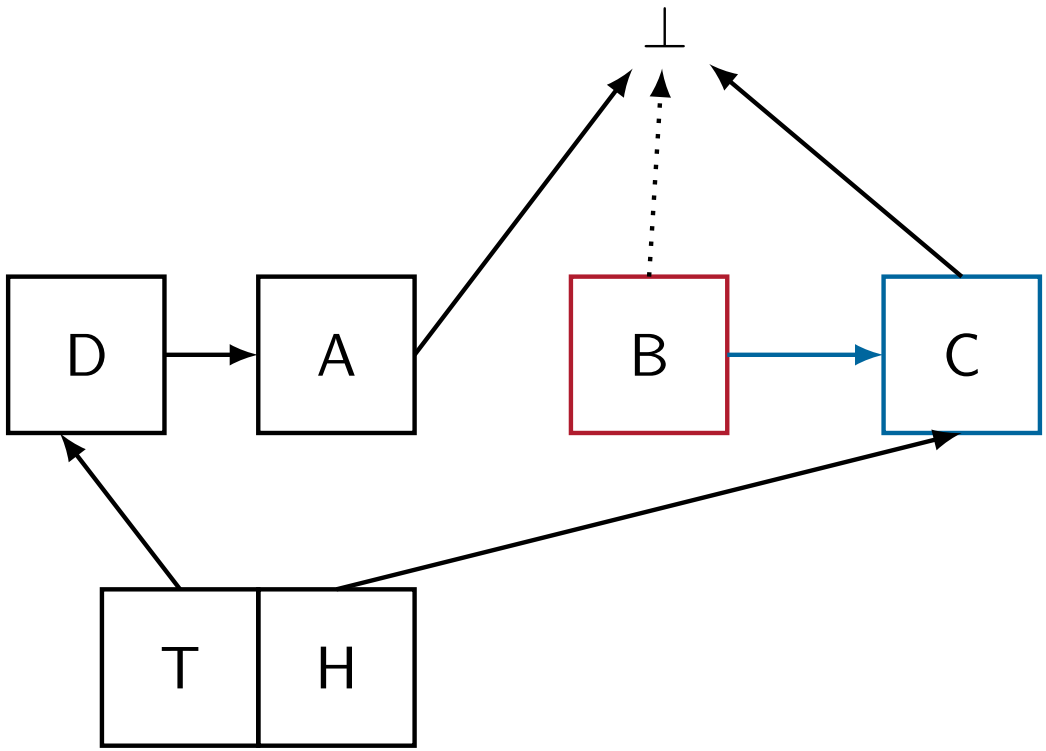


Queue implementation



Queue implementation



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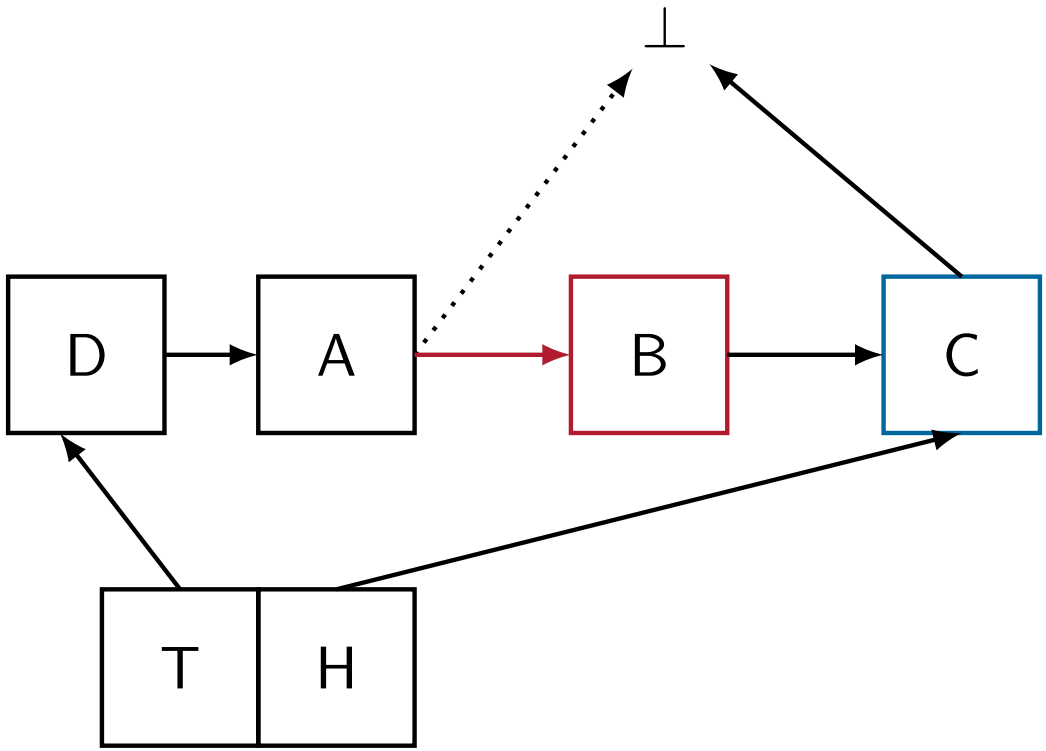
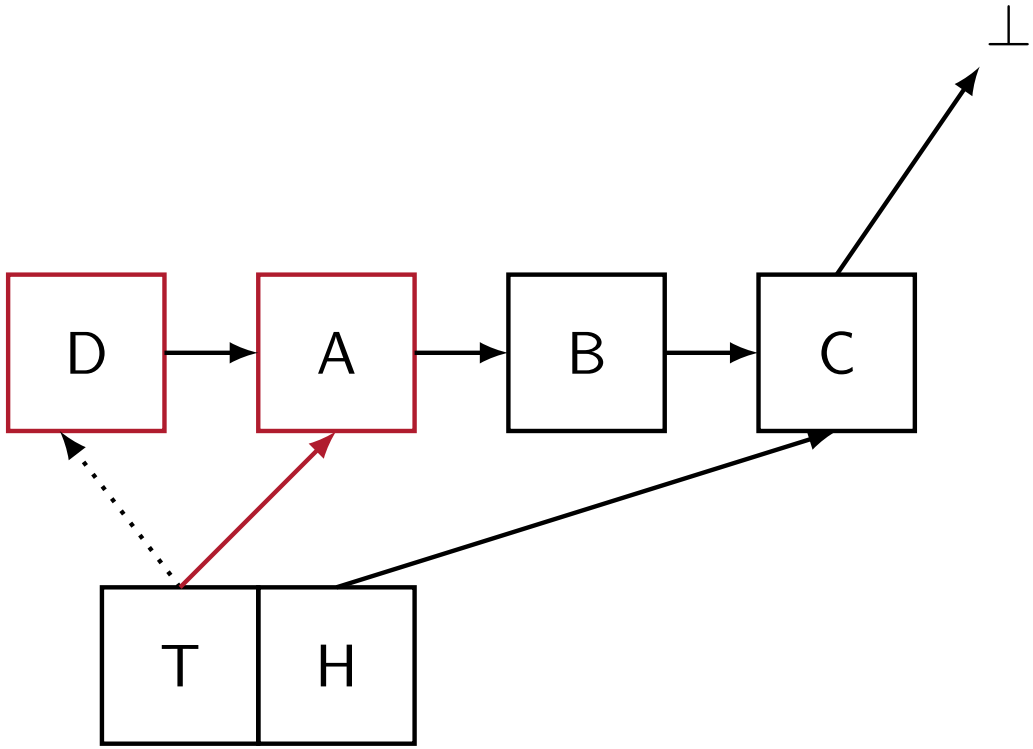
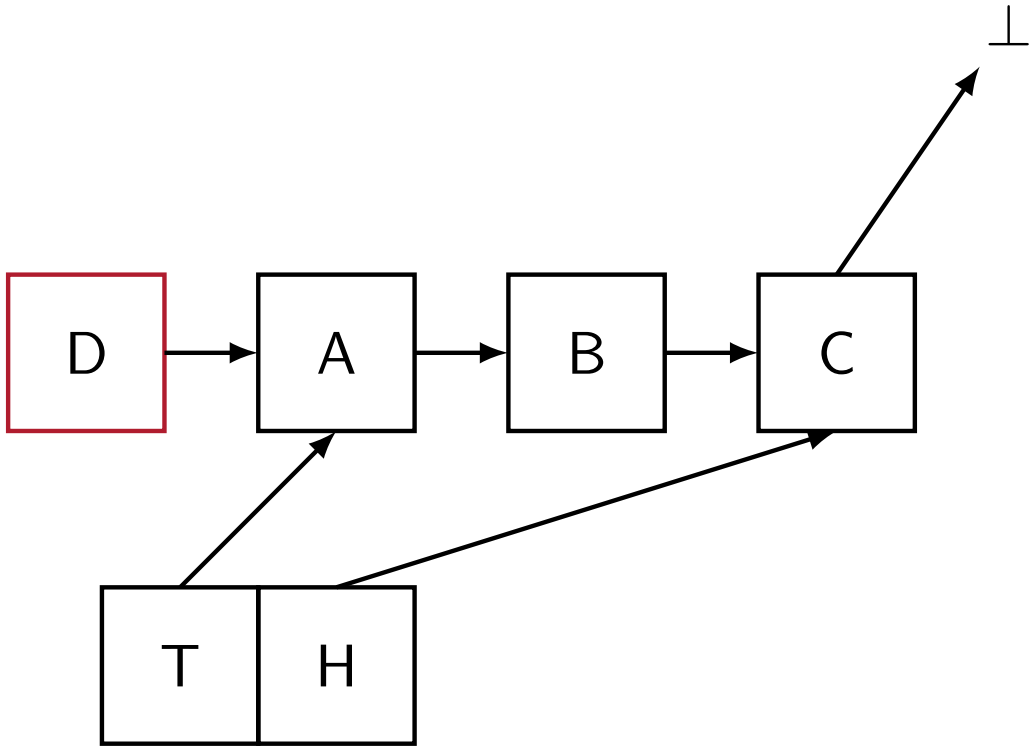


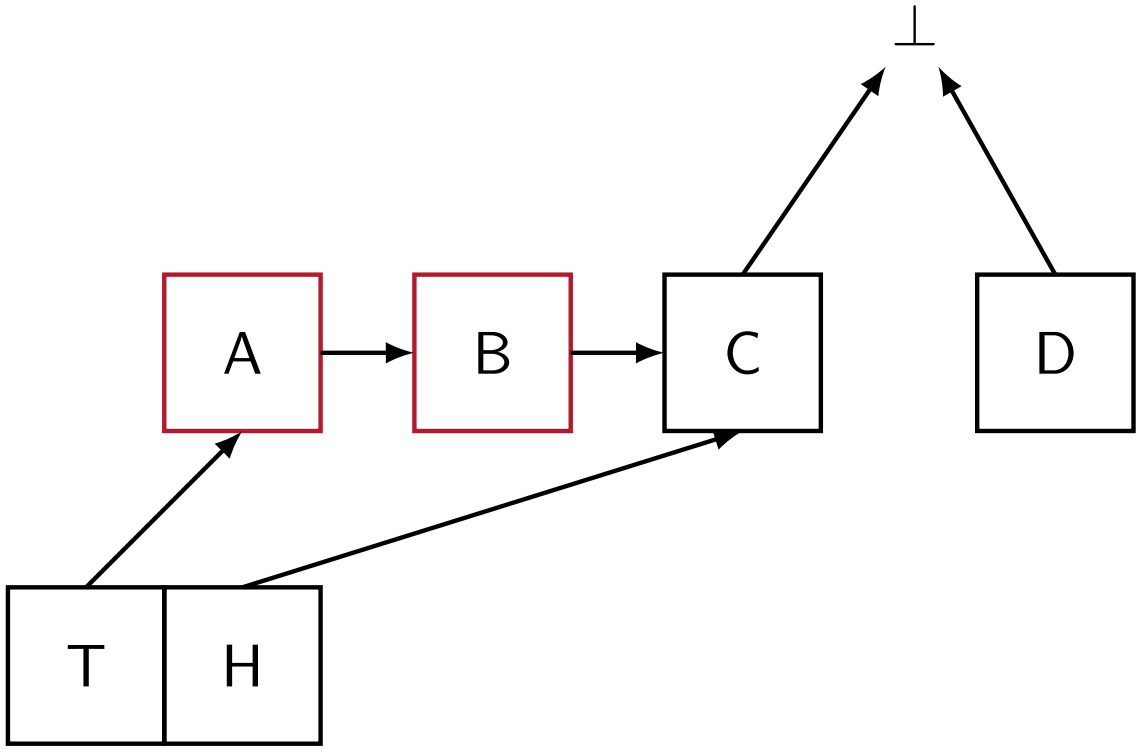
Queue implementation



Queue implementation



Queue implementation



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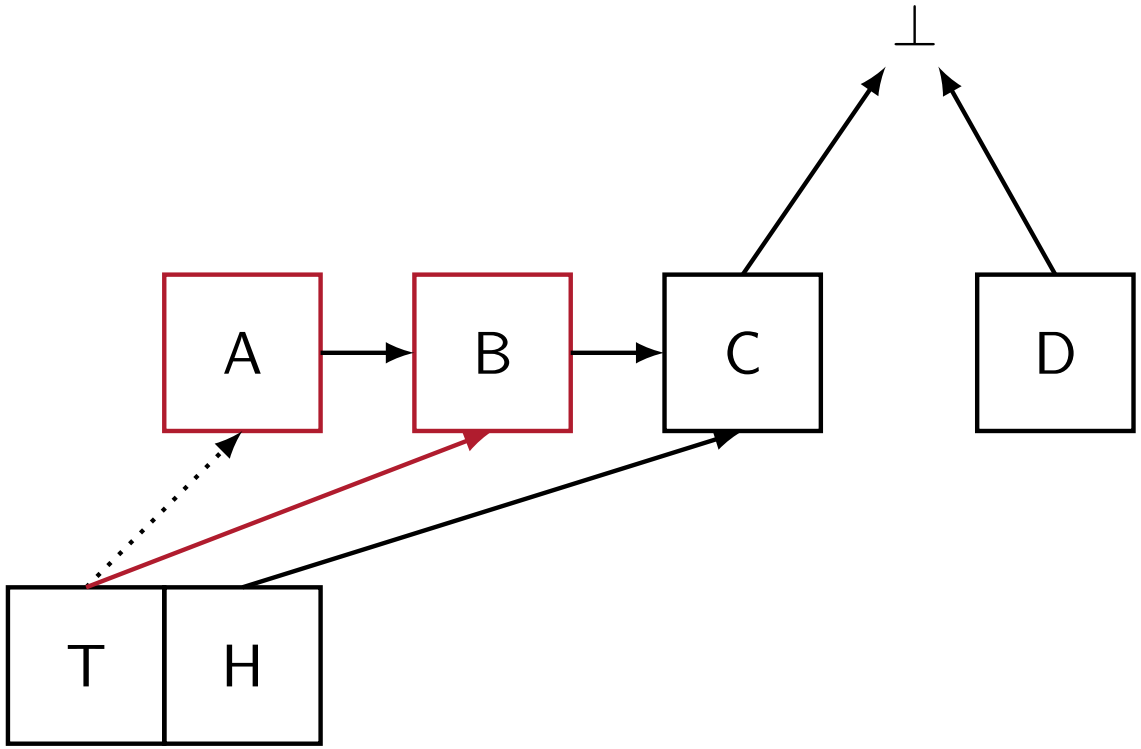

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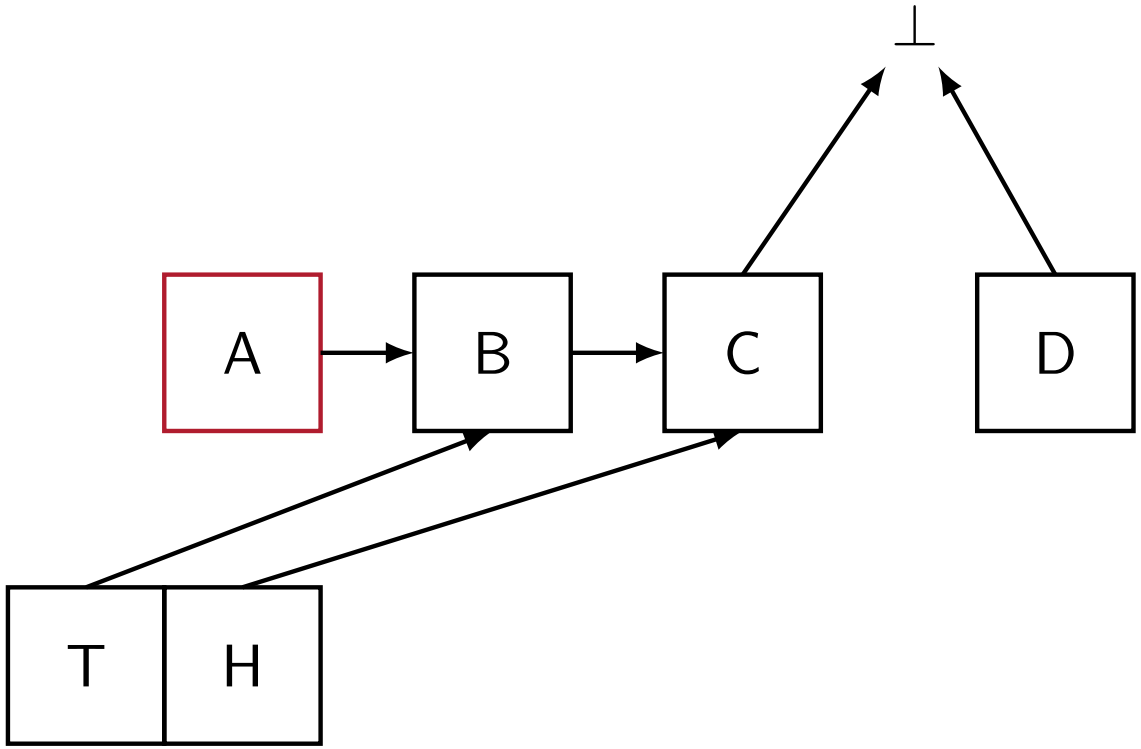

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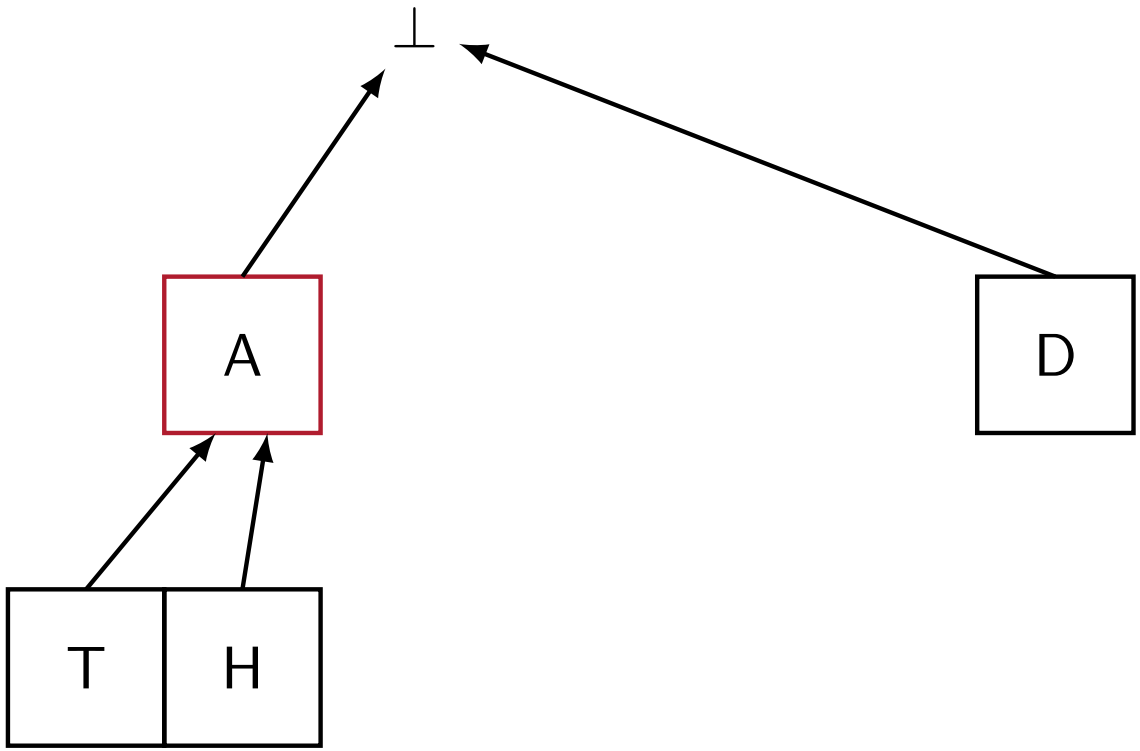

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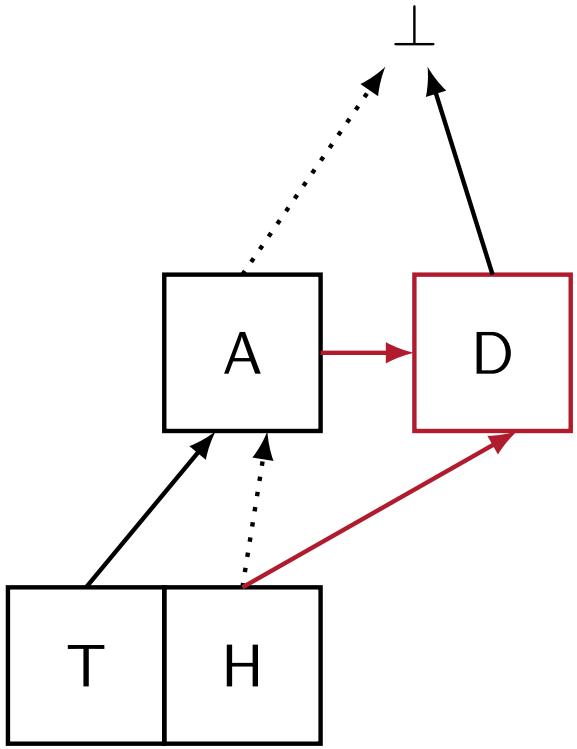

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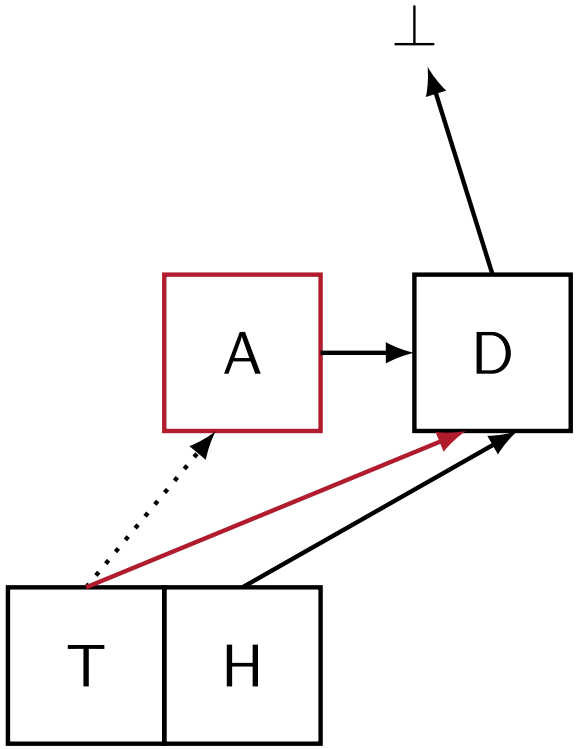

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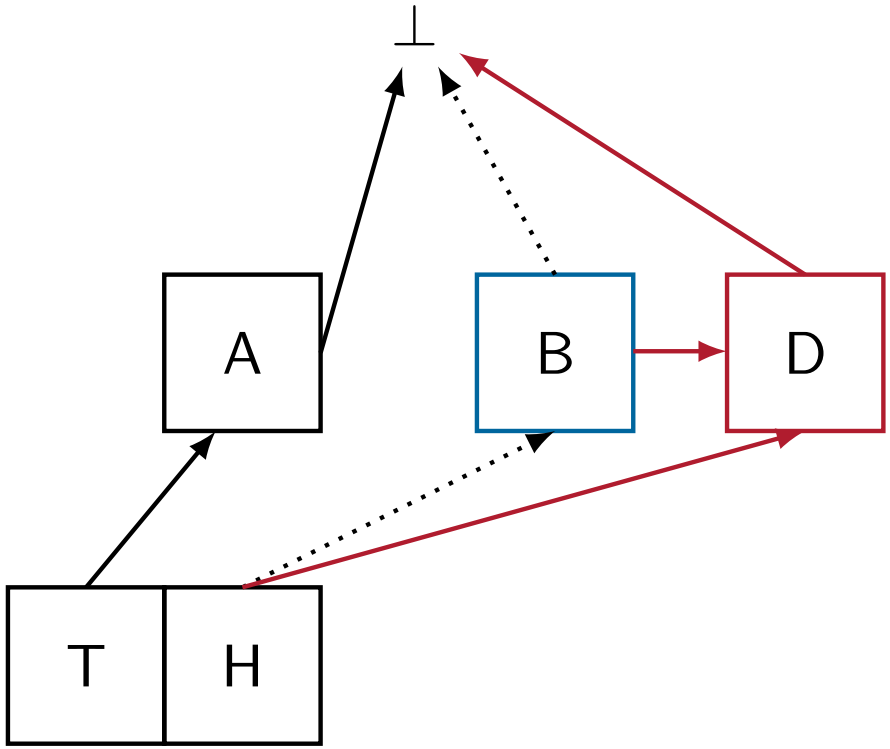

Agenda

Non-Blocking Data Structures

Lock-free Events

Worker Thread Notification

Assignment 5

Wait for a condition

- Actively or Inactively ("passive")
  - Does the thread release the processor core?
  - Different performance, energy characteristics, ...
- Active waiting ...
  - Is usually fast, except for cache contention
  - Causes relatively high energy consumption
  - Probably wastes CPU time
- Passive waiting ...
  - Tends to be more energy-efficient
  - Supports many-threaded system

  → More threads than cores

Eager event

- No thread management data

```
1 typedef struct event {
2   atomic_int state;
3 } event;
```

- Eager check for condition

```
1 void event_await(event *e) {
2   while (PENDING == atomic_load(&e->state));
3 }
```

← acquire

- Notification by assignment

```
1 void event_signal(event *e) {
2   atomic_store(&e->state, PAST);
3 }
```

← release

Passive waiting done wrong

How not to wait for a condition

```
1  void event_await(event *e) {
2    while (PENDING == atomic_load(&e->state))
3      sleep();
4  }
```

Lost-wakeup problem

- Critical section between `load()` and `sleep()`
- Concurrent notification is lost
- Need for atomic `test_and_sleep()` operation

Passive waiting

How to wait for a condition passively?

- Data race between condition check and sleep instruction
- Atomic operation required
  - x86: `monitor`, `mwait` (privileged [1])
  - Linux: `futex()` system call

Linux `futex` interface

```
1 syscall(SYS_futex, addr, FUTEX_WAIT, exp, &timeout);
2 syscall(SYS_futex, addr, FUTEX_WAIT, exp, NULL);
3 syscall(SYS_futex, addr, FUTEX_WAKE, num_threads);
4 ...
```

Problem of spurious wakeup

- Threads can wake up despite not being signalled
- Need for re-evaluation of waiting conditions

Linux futex semantics

Wait until a variable changes

```
1  void futex_wait(int *addr, int exp) {
2    if (*addr == exp)
3      sleep_on(addr);
4  }
```

Address-dependent wakeup function

```
1  void futex_wake(int *addr) {
2    for (Thread *t ← Threads)
3      if (t->waiting_on == addr)
4        wakeup(t);
5  }
```

Linux futex semantics

Wait until a variable changes

```
1  void futex_wait(int *addr, int exp) {
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atomic

Address-dependent wakeup function

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```

Linux `futex` usage pattern

- `futex` usage pattern

```
int i = atomic_load(&v);
futex_wait(&v, i);
```

```
atomic_store(&v, j);
futex_wake(&v);
```

- Critical Section
  - Between `atomic_load()` and `futex_wait()`
  - Concurrent signal must be caught

Linux futex usage pattern

- futex usage pattern

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- futex overlapping patterns

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- Critical Section
  - Between atomic_load() and futex_wait()
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- futex overlapping patterns

```
int i = atomic_load(&v);



futex_wait(&v, i);
```

```


atomic_store(&v, j);
futex_wake(&v);
```

Simple futex-based event

- Glibc has no direct SYS_futex wrapper

```
1 #define futex(...) syscall(SYS_futex, __VA_ARGS__)
```

- wait-operation using a futex

```
1 void event_await(event *e) {
2   while (PENDING == atomic_load(&e->state))
3     futex((int *) &e->state,
4           FUTEX_WAIT, PENDING, NULL);
5 }
```

- signal-operation on a futex

```
1 void event_signal(event *e) {
2   atomic_store(&e->state, PAST);
3   futex((int *) &e->state, FUTEX_WAKE, INT_MAX);
4 }
```

Simple futex-based event

- Glibc has no direct SYS_futex wrapper

```
1 #define futex(...) syscall(SYS_futex, __VA_ARGS__)
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- wait-operation using a futex

```
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- signal-operation on a futex

```
1 void event_signal(event *e) {
2   atomic_store(&e->state, PAST);
3   futex((int *) &e->state, FUTEX_WAKE, INT_MAX);
4 }
```

ABA-safe `futex`-based event

- Use larger state space

```
1  #define is_pending(x) (!((x)&1))
```

- Conditionally wait on variable change

```
1  void event_await(event *e) {
2    int val = atomic_load(&e->state);
3    if (!is_pending(val))
4      return;
5    do {
6      futex((int *) &e->state, FUTEX_WAIT, val, NULL);
7    } while (atomic_load(&e->state) == val);
8  }
```

ABA-safe `futex`-based event (2)

Conditionally increment state variable

```
1  void event_signal(event *e) {
2    int val = atomic_load(&e->state);
3    if (!is_pending(val)) return;
4    if (atomic_compare_exchange_strong(&e->state,
5                                       &val, val + 1))
6      futex((int *) &e->state, FUTEX_WAKE, INT_MAX);
7  }
8  void event_reset(event *e) {
9    int val = atomic_load(&e->state);
10   if (is_pending(val)) return;
11   atomic_compare_exchange_strong(&e->state,
12                                  &val, val + 1);
13 }
```

Agenda

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Worker Thread Notification

Assignment 5

Worker thread waiting condition

- Similar to `event` implementation
  - Unilateral synchronisation
  - Correctness depends on job queue consistency
- Implementation variants
  - `sensitivity` flag
    → Wait while `sensitive` $\neq 0$
  - `load` counter
    → Wait for `load` $\neq 0$
  - `generation` counter
    → Wait for `generation` increment
  - ...

Worker thread waiting condition – sensitivity flag

- Get next Job

```
1  job *next() {
2    atomic_store(&sensitive, 1); // single consumer!
3    job *n = dequeue();
4    if (n)
5      return atomic_store(&sensitive, 0), n;
6    futex((int *) &sensitive, FUTEX_WAIT, 1, NULL);
7    return next();
8  }
```

- Submit a job

```
1  void submit(job *j) {
2    enqueue(j); int old = 1;
3    if (atomic_compare_exchange_strong(&sensitive,
4                                       &old, 0))
5      futex((int *) &sensitive, FUTEX_WAKE, 1);
```

Worker thread waiting condition – load counter

- Get next Job

```
1  job *next(){
2    while (!atomic_load(&load))
3      futex((int *) &load, FUTEX_WAIT, 0, NULL);
4    atomic_fetch_sub(&load, 1); // single consumer!
5    return dequeue();
6  }
```

- Submit a job

```
1  void submit(job *j) {
2    enqueue(j);
3    if (!atomic_fetch_add(&load, 1))
4      futex((int *) &sensitive, FUTEX_WAKE, 1);
5  }
```

Worker thread waiting condition – generation counter

- Get next Job

```
1  job *next() {
2    int now = atomic_load(&generation);
3    job *n = dequeue();
4    if (n)
5      return n;
6    futex((int *) &generation, FUTEX_WAIT, now, NULL);
7    return next();
8  }
```

- Submit a job

```
1  void submit(job *j) {
2    enqueue(j);
3    atomic_fetch_add(&generation, 1);
4    futex((int *) &generation, FUTEX_WAKE, INT_MAX);
5  }
```

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Assignment 5

Assignment 5

- Rewrite LWT without locks
  - Remove all scheduler locks ...
  - ... but still provide high-level synchronisation for LWT threads
- Tackle the ABA problem
  - Use version counters where needed
- All LWT synchronisation mechanisms use futexes internally
  - Internal `lwt_futex` data structure
  - Used by mutexes, condition variables, semaphore, `join()`, ...
  - Only one mechanism for passive waiting / thread blocking
- Logical cores use the `futex` system call for passive waiting
  - Sleep when no `lwt_thread` is ready

Reference List I

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Intel Architecture Software Developer's Manual.
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[6] Yang, C. ; Mellor-Crummey, J. :
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