Concurrent Systems

Exercise 05 – Non-Blocking Synchronisation

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2021-01-21

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]

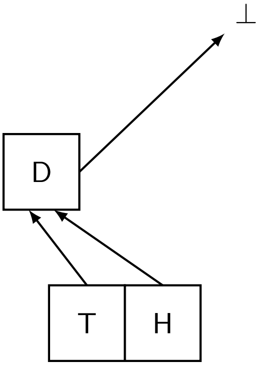
- Minimal interface
  - At least `enqueue()` and `dequeue()`
  - Sometimes `is_empty()`, `make_empty()`

- Differences between lock-free queue algorithms [5]
  - Single-producer ↔ Multi-producer
  - Single-consumer ↔ Multi-consumer
  - Lock-free ↔ Wait-free
  - Nonintrusive ↔ intrusive
  - Node-based ("Unbounded") ↔ Array-based ("bounded") ↔ Hybrid
  - Consistency guarantees
  - ...

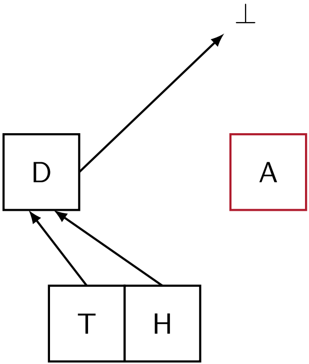
Queue example

- 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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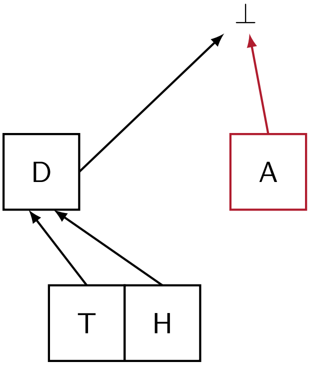

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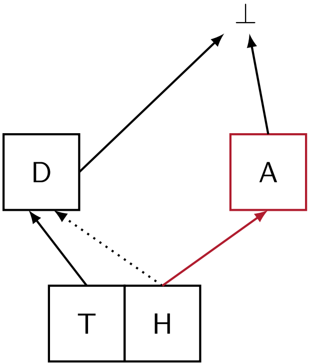

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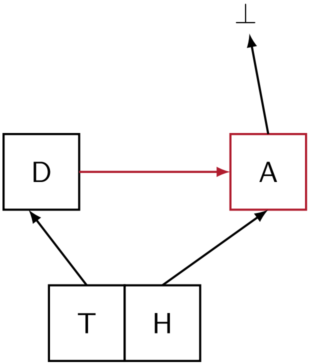

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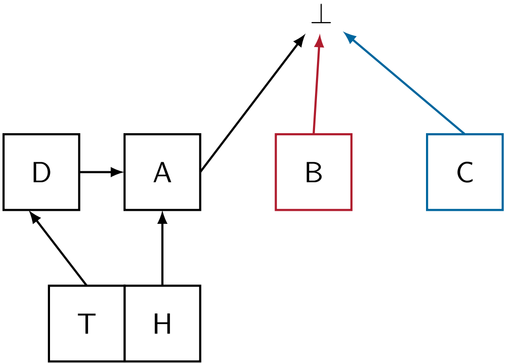

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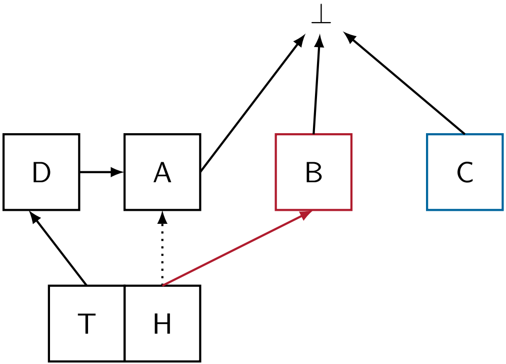

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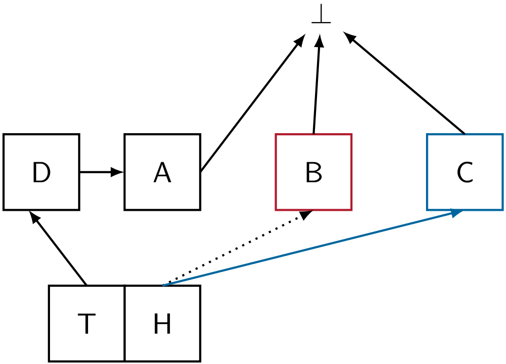

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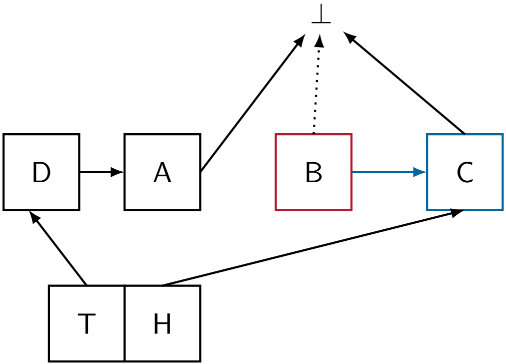

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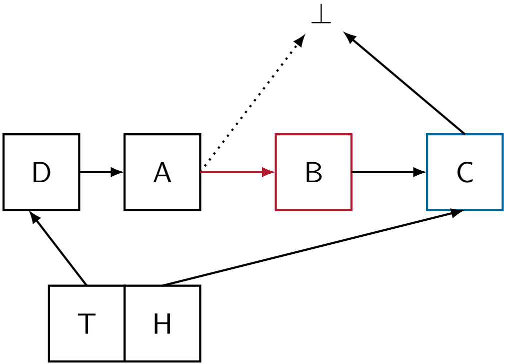

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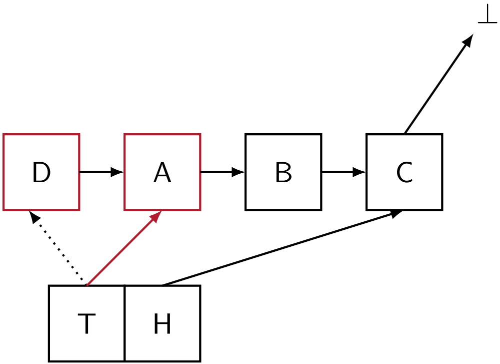

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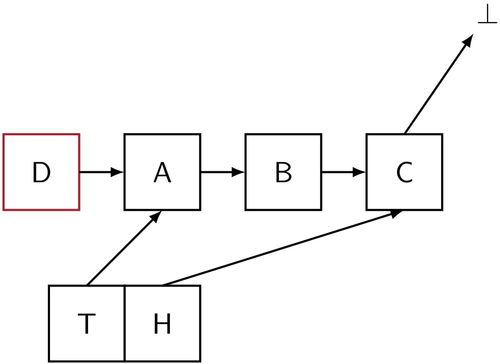

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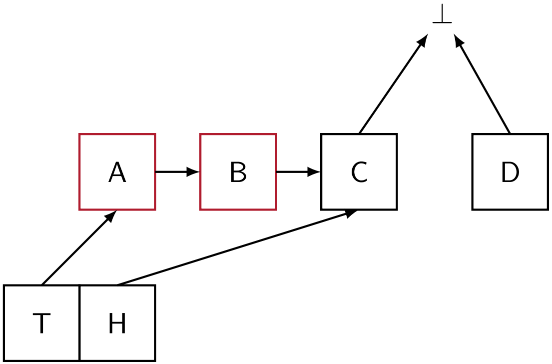

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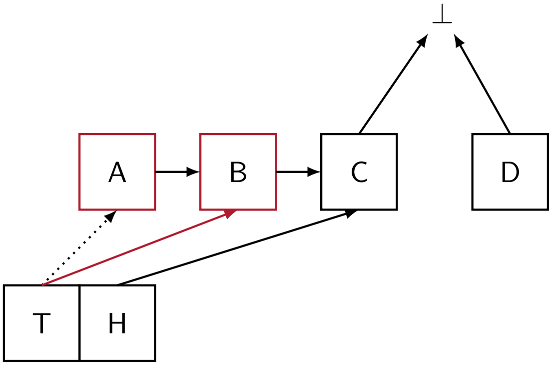

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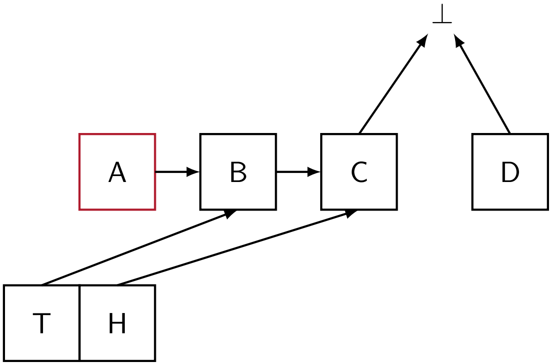

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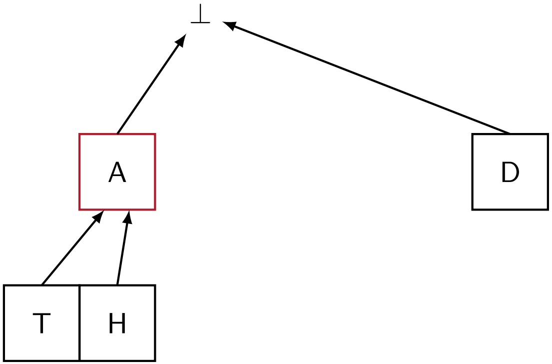

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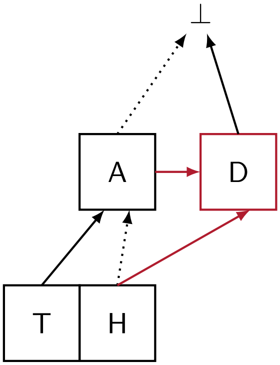

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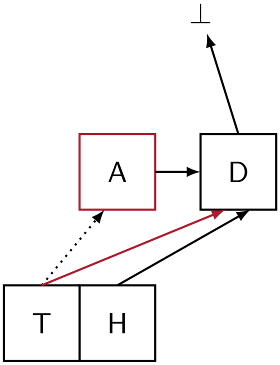

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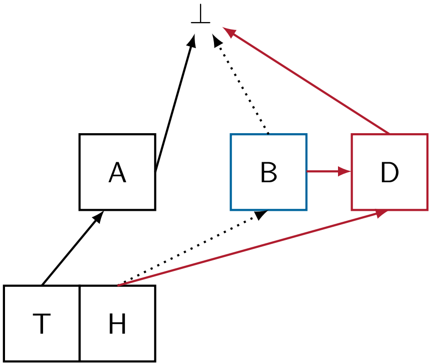

Agenda

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

```
typedef struct event {
  atomic_int state;
} event;
```

- Eager check for condition

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

- Notification by assignment

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

Passive waiting done wrong

How not to wait for a condition

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

✗

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

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

- 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

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

- Address-dependent wakeup function

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

Linux futex semantics

- Wait until a variable changes

```
void futex_wait(int *addr, int exp) {
  if (*addr == exp)        ] atomic
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Linux futex usage pattern

- futex usage pattern

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

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

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

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- futex overlapping patterns

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


atomic_store(&v, j);
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Linux futex usage pattern

futex usage pattern

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

- Between `atomic_load()` and `futex_wait()`
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futex overlapping patterns

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

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atomic_store(&v, j);

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- futex usage pattern

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futex_wake(&v);
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- Critical Section
  - Between atomic_load() and futex_wait()
  - Concurrent signal must be caught

- 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

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

- wait-operation using a futex

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

- signal-operation on a futex

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

Simple futex-based event

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

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void event_await(event *e) {
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- signal-operation on a futex

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

- ABA-Problem?

→ reset() operation available?

ABA-safe futex-based event

- Use larger state space

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

- Conditionally wait on variable change

```
void event_await(event *e) {
  int val = atomic_load(&e->state);
  if (!is_pending(val))
    return;
  do {
    futex((int *) &e->state, FUTEX_WAIT, val, NULL);
  } while (atomic_load(&e->state) == val);
}
```

ABA-safe futex-based event (2)

- Conditionally increment state variable

```c
void event_signal(event *e) {
  int val = atomic_load(&e->state);
  if (!is_pending(val)) return;
  if (atomic_compare_exchange_strong(&e->state,
                                     &val, val + 1))
    futex((int *) &e->state, FUTEX_WAKE, INT_MAX);
}
void event_reset(event *e) {
  int val = atomic_load(&e->state);
  if (is_pending(val)) return;
  atomic_compare_exchange_strong(&e->state,
                                 &val, val + 1);
}
```

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Assignment 5

Worker thread waiting condition

- Similar to event implementation
  - Unilateral synchronisation
  - Correctness depends on job queue consistency

- Implementation variants
  - `sensitivity` flag
    $\rightarrow$ Wait while `sensitive` $\neq 0$
  - `load` counter
    $\rightarrow$ Wait for `load` $\neq 0$
  - `generation` counter
    $\rightarrow$ Wait for `generation` increment
  - ...

Worker thread waiting condition – sensitivity flag

- Get next Job

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

- Submit a job

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

Worker thread waiting condition – load counter

- Get next Job

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

- Submit a job

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

Worker thread waiting condition – generation counter

- Get next Job

```
job *next() {
  int now = atomic_load(&generation);
  job *n = dequeue();
  if (n)
    return n;
  futex((int *) &generation, FUTEX_WAIT, now, NULL);
  return next();
}
```

- Submit a job

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

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- 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

[1] INTEL CORPORATION (Hrsg.):
Intel Architecture Software Developer's Manual.
Santa Clara, California, USA: Intel Corporation, 2016

[2] MICHAEL, M. M. ; SCOTT, M. L.:
Simple, Fast, and Practical Non-blocking and Blocking Concurrent Queue Algorithms.
In: *Proceedings of the 15th Annual ACM Symposium on Principles of Distributed Computing (PODC)*, ACM Press, 1996, S. 267–275

[3] MORRISON, A. ; AFEK, Y. :
Fast Concurrent Queues for x86 Processors.
In: *Proceedings of the 18th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPoPP)*, ACM Press, 2013, S. 103–112

[4] VYUKOV, D. :
Intrusive MPSC node-based queue.
http://www.1024cores.net/home/lock-free-algorithms/queues/intrusive-mpsc-node-based-queue,

[5] VYUKOV, D. :
Producer-Consumer Queues.
http://www.1024cores.net/home/lock-free-algorithms/queues,

Reference List II

[6] Yang, C. ; Mellor-Crummey, J. :
A Wait-free Queue As Fast As Fetch-and-add.
In: *Proceedings of the 21st ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPoPP)*, ACM Press, 2016, S. 16:1–16:13