Concurrent Systems

Exercise 05 – Non-Blocking Synchronization

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2018-01-15

Agenda

Non-Blocking Data Structures

Wait for a Condition

Synchronization with Futexes

Assignment 5

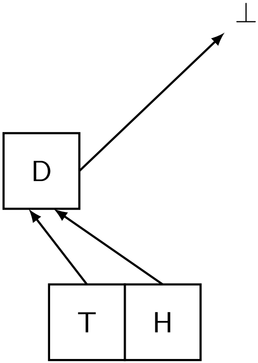
Non-blocking queue

- 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 implementation



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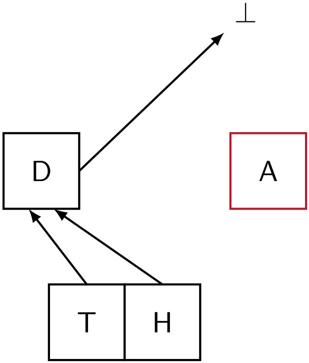

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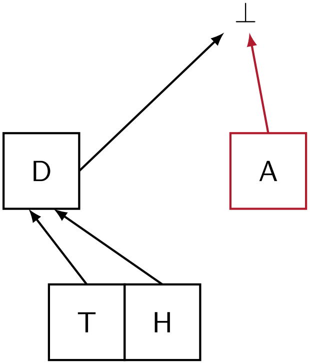

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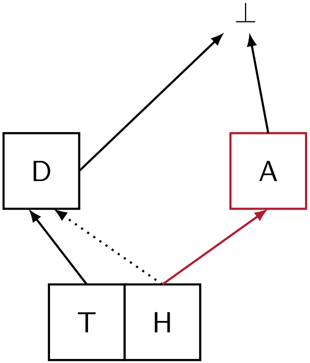

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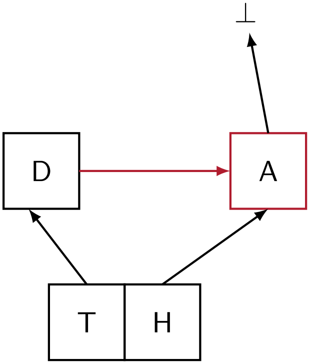

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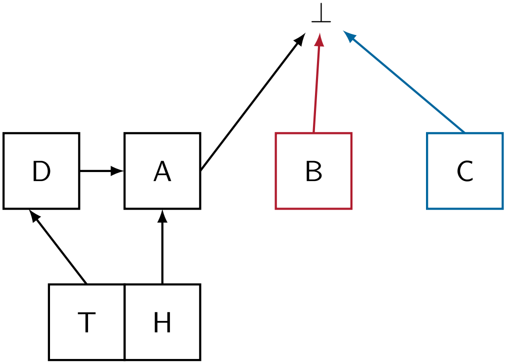

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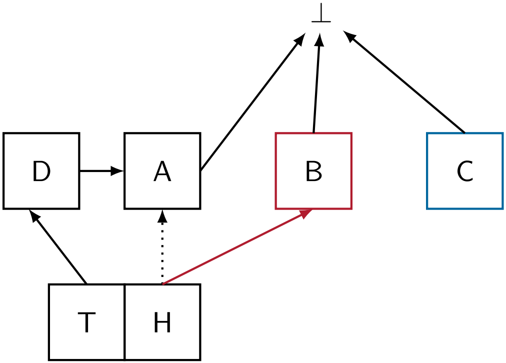

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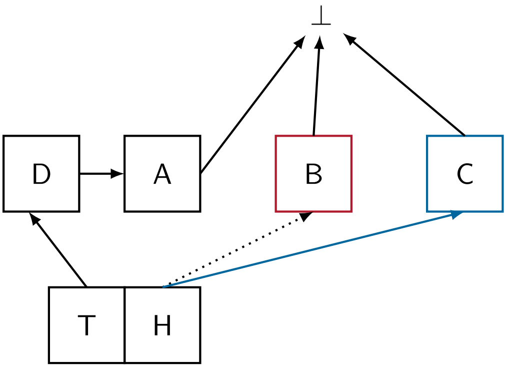

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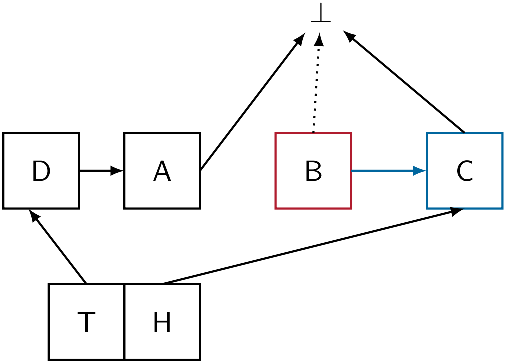

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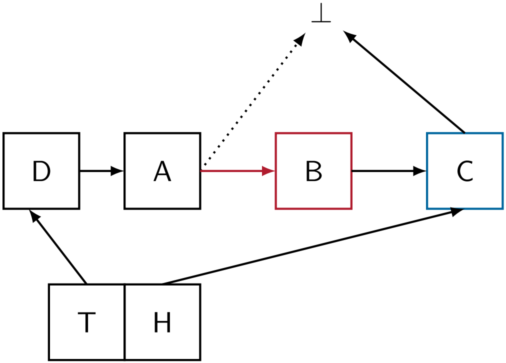

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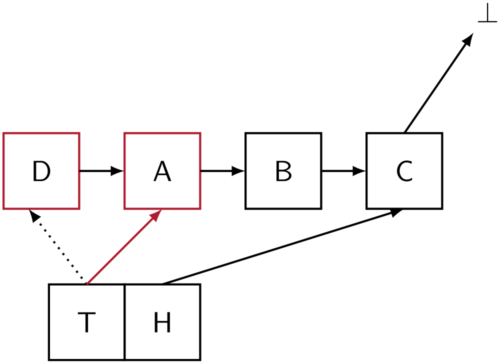

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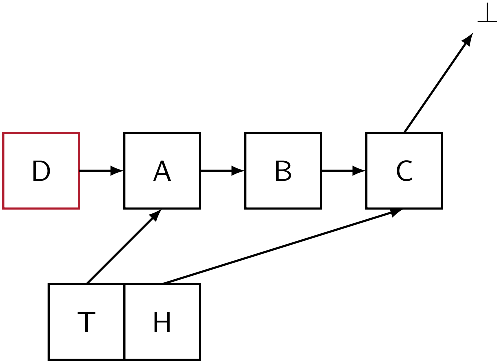

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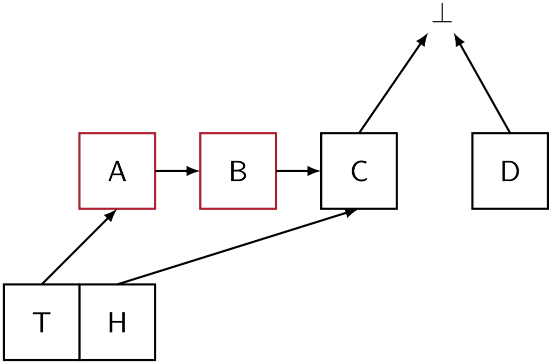

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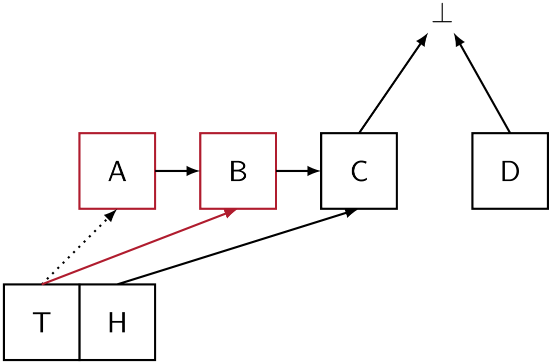

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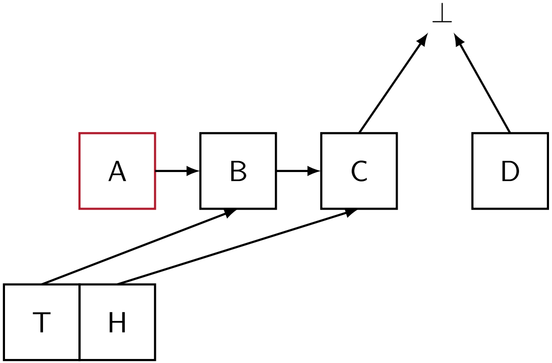

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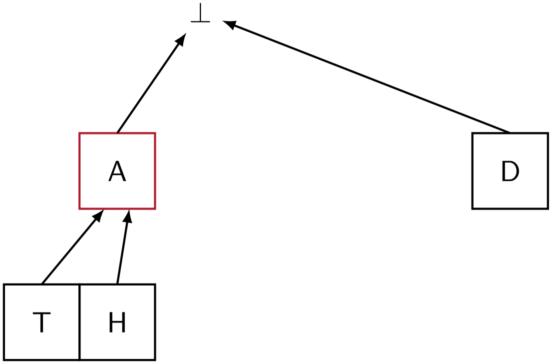

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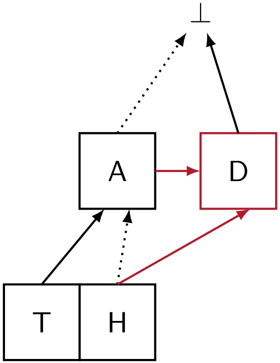

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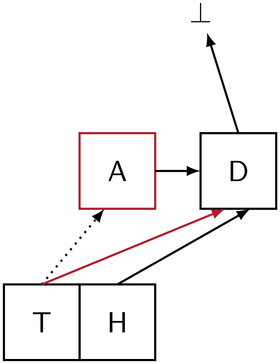

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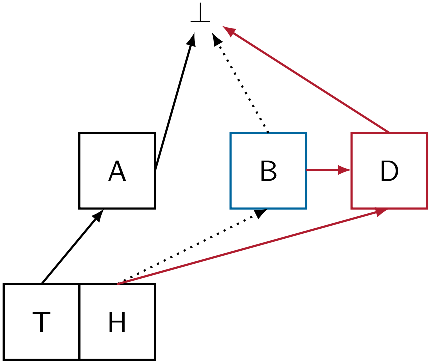

Wait for a condition

- 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

  $\rightarrow$ More threads than cores

Eager event

- No thread management data

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

- Eager check for condition

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

- Notification by assignment

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

Passive waiting done wrong

- How not to wait for a condition

```
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

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

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- futex overlapping patterns

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int i = atomic_load(&v);


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

```

Simple futex-based event

- Glibc has no direct SYS_futex wrapper

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

- wait-operation using a futex

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

- signal-operation on a futex

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

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}
```

- ABA-Problem?

→ reset() operation available?

ABA-safe `futex`-based latch

- 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 latch (2)

- Conditionally increment state variable

```
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);
}
```

Worker thread waiting condition

- Similar to event implementation
  - Unilateral synchronization
  - 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

```c
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

```c
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);
}
```

Assignment 5

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

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Intel Architecture Software Developer's Manual.
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[5] VYUKOV, D. :
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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