User-level threads…

… with threads.

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Threading Models

- **1:1 (Kernel Threading)**
  User contexts correspond directly with their own kernel schedulable entity. Everything does this (e.g. Linux, Windows, Solaris, NetBSD, FreeBSD).
- **N:1 (User Threading)**
  User-level threading multiplexed onto a single kernel context. No kernel awareness of user-level threading structure.
- **M:N (Hybrid)**
  Kernel assisted N:1 threading, using M kernel contexts. Classic example is *Scheduler Activations*

Parallel programming models

- Synchronous (Thread/Request)
- Delegate Event (Asynchronous callbacks)
- Message passing / Event Loops

Callback Types

- **Asynchronous callbacks** do not block their caller. They are typically run either within a separate thread, or after their invoker's completion. e.g.:

  ```
  Executor()->Add(Callback(...))
  ```

- **Synchronous callbacks** are always completed (often within the same thread) before control is returned to the caller. e.g.:

  ```
  foo->Lookup(&context, arg, &result);
  ```

Complexity: “Own” vs “View”

```
int x;

(1) Foo(&x);
        vs
(2) Executor()->Add(Callback(Foo, &x));
```

In (2), the reader must immediately be concerned with:

- Synchronization of access to **x.**
- Co-ordination of **x’s** lifetime.
- What happens after **Foo** completes?

Callbacks are not a Programming Model

- Threads are base unit of concurrency... **but**
- **Requests** are the typical “currency” servers must build parallelism around.

Programming Models: Thread per request

Advantages

- Simple programming model
- Good data-locality

Challenges

- Harder to realize parallelism within a request
- *Latency predictability varies inversely with load*
    - **1000 outstanding requests means 1000 threads. Do you know where your threads are?**

Programming Models: Asynchronous Worker Objects

Advantages
- Greater control of work partitioning, improved latency predictability.
- Lower overheads achievable.

Challenges
- *Complex programming model*; control and data-flow now require encapsulation. No longer strictly linear. Additional resource boundaries introduced. Code written under this model depends more heavily on primitives such as *Conditions.*
- Loss of data locality.

Crux

crux, n: something that torments by its puzzling nature; a perplexing difficulty.

We **'fixed'** thread-per-request by introducing concurrency objects that are smaller than a request.

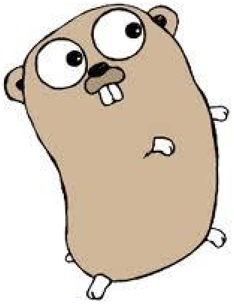
... yet many of thread-per-requests issues caused by concurrency!

... communication still cumbersome.

CSP: Go's take

Go provides constructs allowing for a more synchronous model; allowing control flow to be represented in a linear fashion, while realizing available concurrency.

Key features:
- Goroutines
- Channels
- Select statement



What makes this type of model hard to achieve in C++?

Where does this hybrid face challenges? Are they barriers to adoption within C++?

How much does a context switch cost?

```
~# for ((i=0;i<10;i++)) do time .
/pipe_test 500000; done
real     0m2.911s
real     0m3.052s
real     0m5.282s
real     0m4.724s
real     0m6.780s
real     0m1.250s
...
```

Why the inconsistency?

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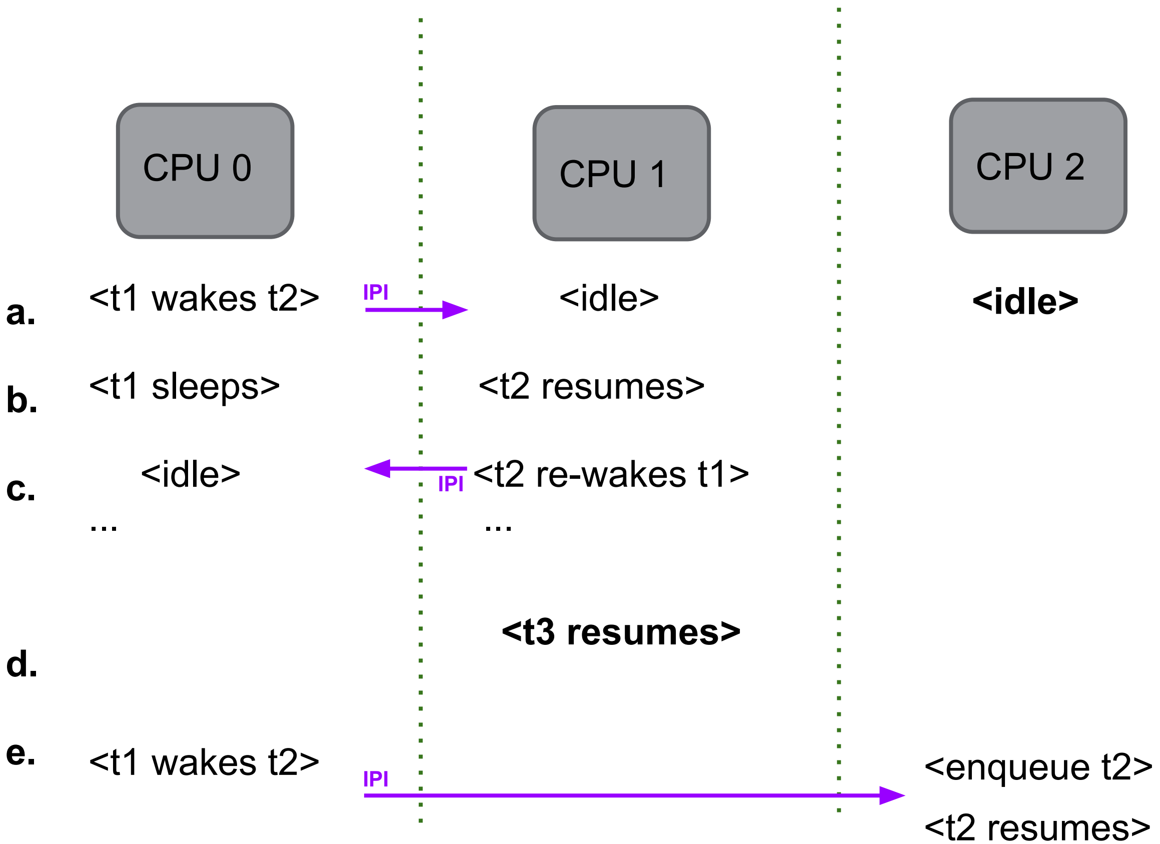
How about a raw futex?

- sys_futex() allows a program to wait for an address to change, or signal anyone waiting on a given address.
-
```
Benchmark      Time(ns)  CPU(ns) Iterations
----------------------------------------------
BM_Futex                  4705      3555   1000000
BM_Futex                  2757      1917   1000000
BM_Futex                  2931      1983   1000000
BM_Futex                  2791      1935   1000000
BM_Futex                  2932      1933   1000000
```
- A little faster, ~2.7 usec/switch typical.

Wake-up CPU interactions



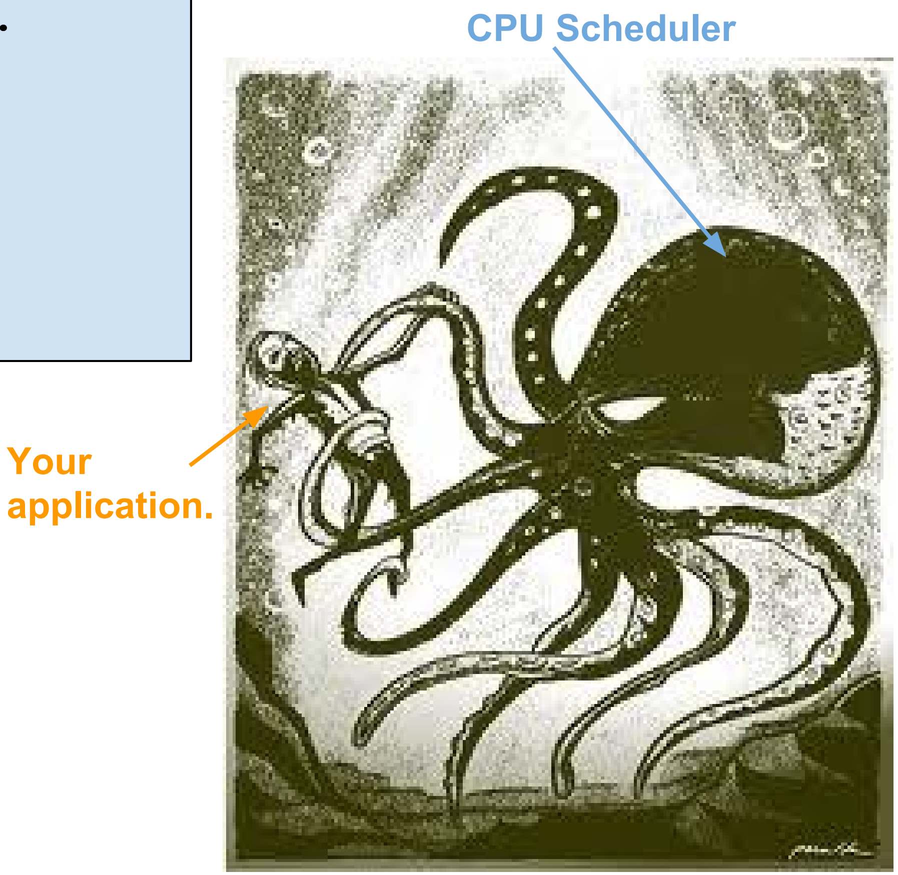
So what's the true cost?

```
ibsy1:~# taskset -c 0 time  .
/pipe_test 500000

real    0m1.326s
user    0m0.055s
sys     0m0.635s
```

1 million context switches
~1.326 usec per switch

Can we do better?



Futex (pinned)

Benchmark	Time(ns)	CPU(ns)	Iterations
BM_Futex	1028	1022	1000000
BM_Futex	1030	1024	1000000
BM_Futex	1021	1016	1000000
BM_Futex	1022	1016	1000000
BM_Futex	1012	1006	1000000

Down to ~1 usec, getting better.. but little else we can do.

Context-switch cost: key observations

- The switch into kernel mode *(ring0)* is surprisingly inexpensive
  - **<50ns round trip.**
- Majority of the context-switching cost attributable to the complexity of the scheduling decision by a modern SMP cpu scheduler.

Syscall API

`pid_t switchto_wait(timespec *timeout)`

- Enter an 'unscheduled state', until our control is re-initiated by another thread or external event (signal).

`void switchto_resume(pid_t tid)`

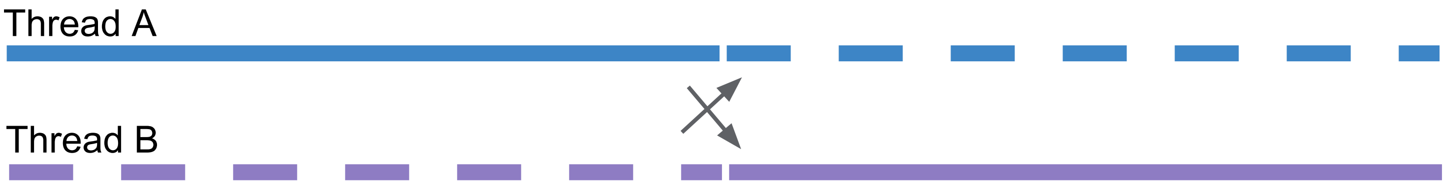
- Resume regular execution of tid

`pid_t switchto_switch(pid_t tid)`

- Synchronously transfer control to target sibling thread, leaving the current thread unscheduled.
- Analogous to:
    - *Atomically { Resume(t1); Wait(NULL); }*

Kernel View

CPU i:



Minimal scheduling operation.

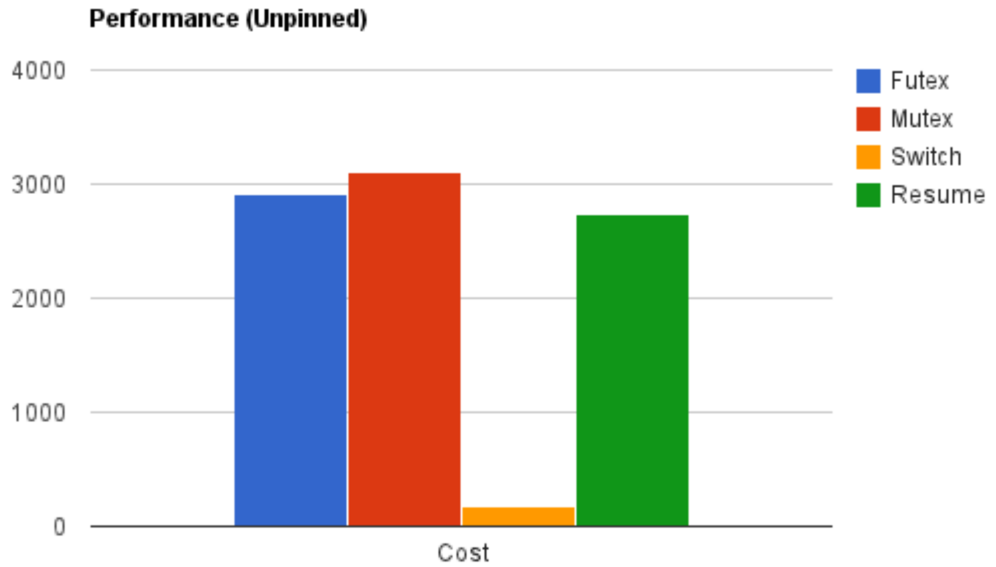
- B inherits A's virtual runtime.
- B was not runnable, so we don't need to remove it from runqueues.
- B holds references on same objects as A.

(Unscheduled state is *TASK_INTERRUPTIBLE* with a special return stack.)

API choices/Considerations

- Operations must be commutative (reversible).
  {T1:Wait, T2:Switch(T1)} should behave the same as {T2:Switch (T1), T1:Wait}
- Requiring a re-entrant (asynchronous) user-scheduler entry classically hard; prefer a synchronous programming model.
- User scheduling id compatible with kernel scheduling; the kernel scheduler grants us quanta, we schedule *within* that quanta.
- Load-balancing is best left to the load-balancer.

Context-switch performance




```
Benchmark                  Time(ns)   CPU(ns)  Iterations
-----------------------------------------------------
BM_Futex                       2905      1958     1000000
BM_GoogleMutex                 3102      2326     1000000
BM_SwitchTo                     179       178     3917412
BM_SwitchResume                2734      1554     1000000
```

Advantages of maintaining a 1:1 threading model

- Semantics dependent on thread identity (e.g. TLS, tid, etc) are preserved.
- Existing debugging and profiling tools work naturally.
- Existing thread management APIs (e.g. nice(2), tkill) continue to work.
- **Compatible with existing code.**

Related: Socket locality

- Thread A makes request, sends on socket, waits on response
- Response comes to Thread B, a networking thread
- B needs to wake A
  - B would like A to run on the same CPU (locality)

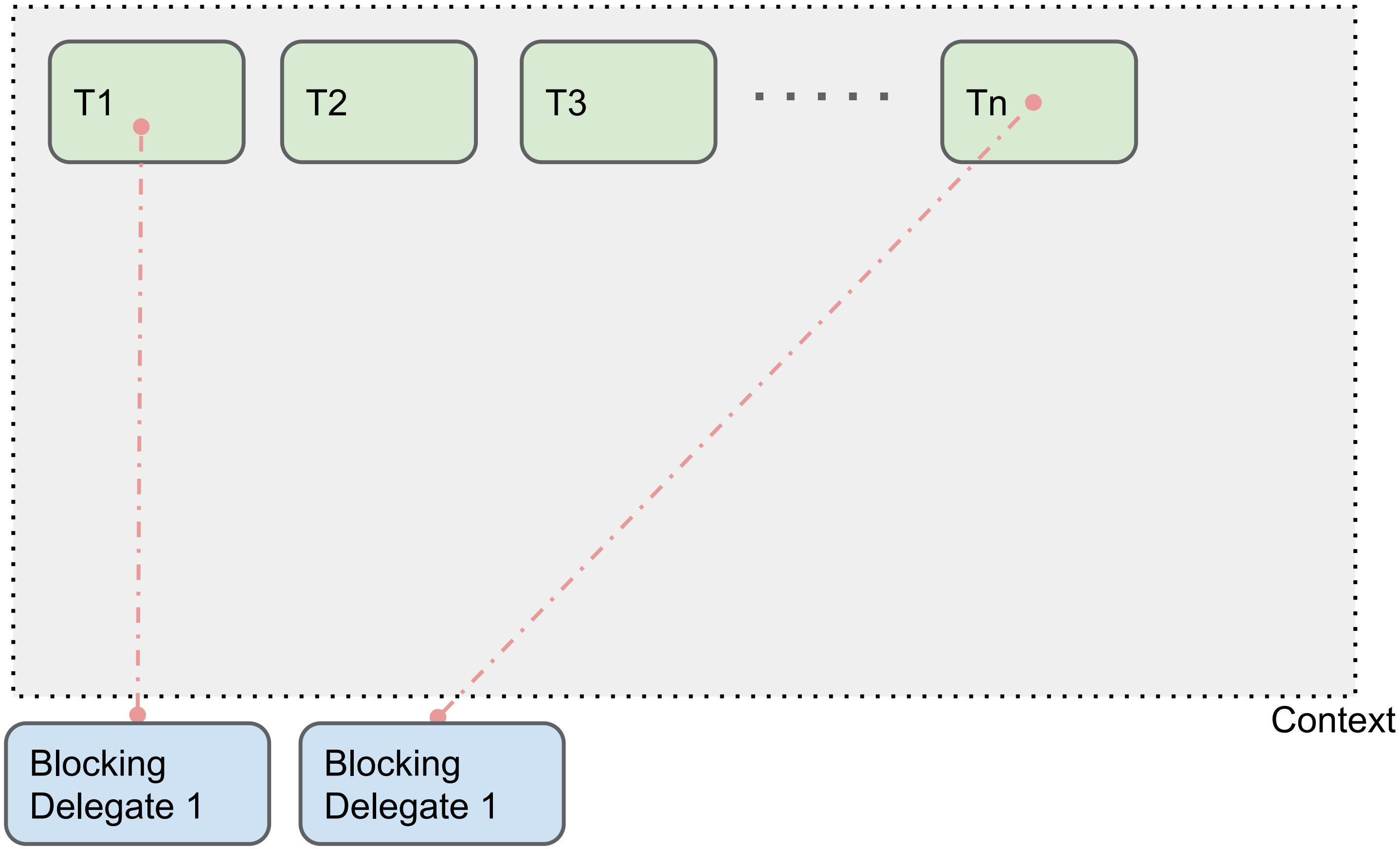
Context-switching lacks context

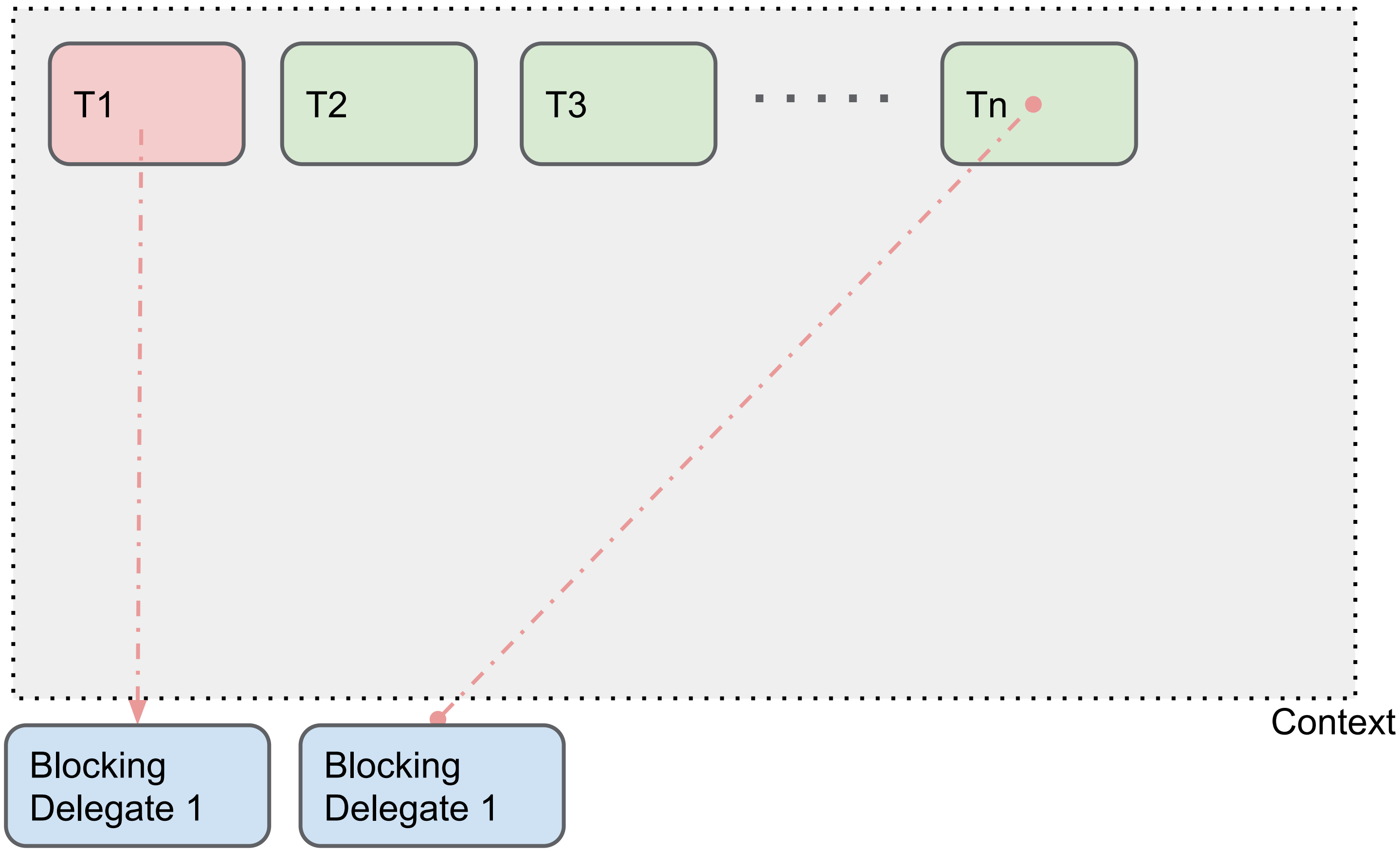
```
static void ContextSwitcher(Mutex* m, ...) {
  for (; n > 0; n--) {
    a) m->LockWhen(Condition(own_mutex(), val));
    b) <mutex_owner = next thread>; m->Unlock();
  }
}
```

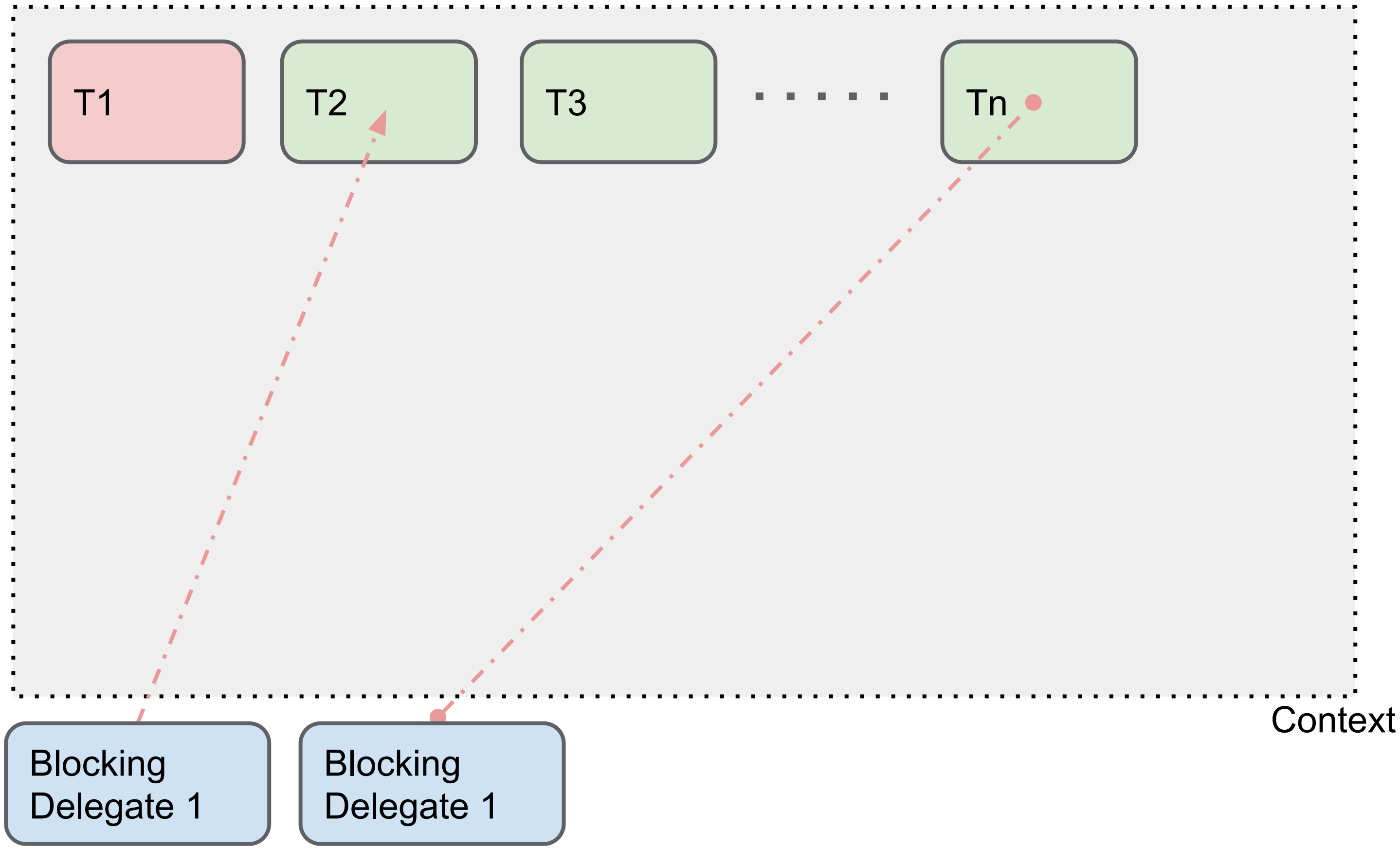
- When releasing resource, no way of advertising that our execution is about to stop.

Backup

Managed Concurrency: SwitchToGroups




T1
T2
T3
Tn
Context
Blocking Delegate 1
Blocking Delegate 1


T1
T2
T3
Tn
Context
Blocking
Delegate 1
Blocking
Delegate 1

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Managed Concurrency

1. **t1:u** read(2) → **t1:k** blocks → SwitchTo → **tD:k**
   IF IDLE:
   a. **tD:u** No other threads → WaitForUnblockingOrNew()
   b. **t1:k** read returns, t1:k allowed to unblock instead of fast-wait
   c. **t1:u** read(2) returns

   ELSE (suppose runnable t2 exists)
   a. ***tD:u*** *→ SwitchTo + BecomeDesignate →* ***t2***
   b. **t2:u** resumes working
   c. (**t1:k** read returns, enters a fast-wait state)

   Since t2 is running (and we chose to have 1 active thread) we've explicitly chosen to defer the processing of t1's wake-up; unlike the 1:1 case, t2's execution proceeds undisturbed, skipping work of the re-enqueue and preemption.