

6.1800 Spring 2025

Lecture #5: Threads

understanding the “most mysterious code” in an OS

6.1800 in the news

Examining Emoji Color Spaces:

A Strategy for Improving the Coverage of Heart Emoji

Author: Jennifer Daniel on behalf of the Unicode Emoji Subcommittee

To: Unicode Technical Committee

Date: November 15, 2020

Last Updated: April 11, 2021



I. Background

Hearts are among the most frequently used emoji. Users of emoji often juxtapose the existing nine colored-heart emoji next to each other to denote markers of emotion, identity or affiliation that are not represented with atomic emoji in the Unicode Standard (ex. Support of Belarus: 🇧🇪🇷🇺🇬🇪, Bisexuality: 🌈💙💜, etc.).¹ It has also recently come to our attention that colored hearts are [the most common emoji used in non-messaging spaces](#) like Twitter bios.

Identifying emoji additions that have multiple-uses is increasingly important as emoji gain in popularity. The more emoji can operate as building blocks instead of specific images the more versatile, fluid, and useful they become.

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how do we decide what
features to add to a system?

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how do we decide what
features to add to a system?

can we correctly predict how
features will be used? who/what
they'll impact?

who gets to make these decisions?

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operating systems enforce modularity on a single machine using **virtualization**

in order to enforce modularity + have an effective operating system, a few things need to happen

- | | | |
|---|--------|--|
| 1. programs shouldn't be able to refer to (and corrupt) each others' memory |→ | virtual memory |
| 2. programs should be able to communicate with each other |→ | bounded buffers
(virtualize communication links) |
| 3. programs should be able to share a CPU without one program halting the progress of the others |→ | assume one program per CPU
(for today) |

operating systems enforce modularity on a single machine using **virtualization**

in order to enforce modularity + have an effective operating system, a few things need to happen

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|---|--------|--|
| 1. programs shouldn't be able to refer to
(and corrupt) each others' memory |→ | virtual memory |
| 2. programs should be able to
communicate with each other |→ | bounded buffers
(virtualize communication links) |
| 3. programs should be able to share a CPU without one program halting the progress of the others |→ | threads
(virtualize processors) |

today's goal: implement **threads**, which allow multiple programs to share a CPU

a **thread** is a virtual processor

a **thread** is a virtual processor
can *suspend* and *resume* a thread

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can *suspend* and *resume* a thread

```
// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    // spin until it's safe to send
    while bb.in - bb.out >= N:
        release(bb.lock)
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

a **thread** is a virtual processor
can *suspend* and *resume* a thread

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// send a message by placing it in bb
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    acquire(bb.lock)
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    while bb.in - bb.out >= N:
        release(bb.lock)
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

question: what are we hoping will happen
in between `release(bb.lock)` and
`acquire(bb.lock)`?



a **thread** is a virtual processor
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// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    // spin until it's safe to send
    while bb.in - bb.out >= N:
        release(bb.lock)
        yield()
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

a **thread** is a virtual processor
can *suspend* and *resume* a thread

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    acquire(bb.lock)
    // spin until it's safe to send
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        release(bb.lock)
        yield()
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

yield()'s job is to suspend the current thread and resume another* thread; our first job today is to understand what that means

*there are cases where `yield()` might suspend the current thread and end up resuming the same thread; that's okay

yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

```
yield():  
    // Suspend the running thread  
    // Choose a new thread to run  
    // Resume the new thread
```

yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

t_lock makes **yield()** an atomic action

```
yield():  
    acquire(t_lock)  
  
    // Suspend the running thread  
    // Choose a new thread to run  
    // Resume the new thread  
  
    release(t_lock)
```

yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

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threads is a table that contains information about each of the current threads

```
yield():
    acquire(t_lock)

    // Suspend the running thread
    // Choose a new thread to run
    // Resume the new thread

    release(t_lock)
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yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

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for each thread it stores the thread's
- state: RUNNABLE, RUNNING

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    acquire(t_lock)  
  
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threads is a table that contains information about each of the current threads

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- state: RUNNABLE, RUNNING
- stack pointer (sp)

```
yield():  
    acquire(t_lock)  
  
    // Suspend the running thread  
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- page table register (ptr)

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for each thread it stores the thread's

- state: RUNNABLE, RUNNING
- stack pointer (sp)
- page table register (ptr)

SP = current stack pointer

PTR = current page table register

```
yield():  
    acquire(t_lock)  
  
    // Suspend the running thread  
    id = id of current thread  
    threads[id].state = RUNNABLE  
    threads[id].sp = SP  
    threads[id].ptr = PTR  
  
    // Choose a new thread to run  
    // Resume the new thread  
  
    release(t_lock)
```

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SP = current stack pointer

PTR = current page table register

CPU = current cpu

```
yield():  
    acquire(t_lock)  
  
    // Suspend the running thread  
    id = cpus[CPU].thread  
    threads[id].state = RUNNABLE  
    threads[id].sp = SP  
    threads[id].ptr = PTR  
  
    // Choose a new thread to run  
    // Resume the new thread  
  
    release(t_lock)
```

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CPU = current cpu

```
yield():
    acquire(t_lock)

    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].state = RUNNABLE
    threads[id].sp = SP
    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
    while threads[id].state != RUNNABLE

    // Resume the new thread

    release(t_lock)
```

yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

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    id = cpus[CPU].thread
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    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
    while threads[id].state != RUNNABLE

    // Resume the new thread
    SP = threads[id].sp
    PTR = threads[id].ptr
    threads[id].state = RUNNING
    cpus[CPU].thread = id

    release(t_lock)
```

yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

```
// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        release(bb.lock)
        yield()
    acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

```
yield():
    acquire(t_lock)

    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].state = RUNNABLE
    threads[id].sp = SP
    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
    while threads[id].state != RUNNABLE

    // Resume the new thread
    SP = threads[id].sp
    PTR = threads[id].ptr
    threads[id].state = RUNNING
    cpus[CPU].thread = id

    release(t_lock)
```

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send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        release(bb.lock)
        yield()
    acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

performance concern: if the processor resumes the sending thread before any thread has called **receive()**, the bounded buffer will still be full, and the sending thread will resume, but immediately **yield** again

```
yield():
    acquire(t_lock)

    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].state = RUNNABLE
    threads[id].sp = SP
    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
    while threads[id].state != RUNNABLE

    // Resume the new thread
    SP = threads[id].sp
    PTR = threads[id].ptr
    threads[id].state = RUNNING
    cpus[CPU].thread = id

    release(t_lock)
```

yield() suspends the running thread, chooses a new thread to run, and resumes the new thread

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// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        release(bb.lock)
        yield()
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
```

it would be nice if send() could indicate “yield, and don’t resume this thread until there’s room in the buffer”

condition variables let threads wait for events (“conditions”), and get notified when they occur. can **wait** on a condition, and be **notified** of it occurring

```
// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
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        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
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    return
```

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```
// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        release(bb.lock)
        wait(bb.has_space)
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    notify(bb.has_message)
    return
```

new variables in use

bb.has_space = indicates that the buffer is not full (and so has space for at least one message)

bb.has_message = indicates that the buffer has at least one message in it

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// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        release(bb.lock)
        wait(bb.has_space)
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    notify(bb.has_message)
    return
```

```
// receive a message from bb
receive(bb):
    acquire(bb.lock)
    while bb.out >= bb.in:
        release(bb.lock)
        wait( ? )
        acquire(bb.lock)
    message <- bb.buf[bb.out mod N]
    bb.out <- bb.out + 1
    release(bb.lock)
    notify( ? )
    return message
```

new variables in use

bb.has_space = indicates that the buffer is not full (and so has space for at least one message)

bb.has_message = indicates that the buffer has at least one message in it

condition variables let threads wait for events (“conditions”), and get notified when they occur. can **wait** on a condition, and be **notified** of it occurring

```
// send a message by placing it in bb
1:  send(bb, message):
2:      acquire(bb.lock)
3:      while bb.in - bb.out >= N:
4:          release(bb.lock)
5:          wait(bb.has_space)
6:          acquire(bb.lock)
7:      bb.buf[bb.in mod N] <- message
8:      bb.in <- bb.in + 1
9:      release(bb.lock)
10:     notify(bb.has_message)
11:     return
```

```
// receive a message from bb
receive(bb):
    acquire(bb.lock)
    while bb.out >= bb.in:
        release(bb.lock)
        wait(bb.has_message)
        acquire(bb.lock)
    message <- bb.buf[bb.out mod N]
    bb.out <- bb.out + 1
    release(bb.lock)
    notify(bb.has_space)
    return message
```

bb.has_space = indicates that the buffer is not full (and so has space for at least one message)

bb.has_message = indicates that the buffer has at least one message in it

condition variables let threads wait for events (“conditions”), and get notified when they occur. can **wait** on a condition, and be **notified** of it occurring

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// send a message by placing it in bb
1:  send(bb, message):
2:      acquire(bb.lock)
3:      while bb.in - bb.out >= N:
4:          release(bb.lock)
5:          wait(bb.has_space)
6:          acquire(bb.lock)
7:      bb.buf[bb.in mod N] <- message
8:      bb.in <- bb.in + 1
9:      release(bb.lock)
10:     notify(bb.has_message)
11:     return
```

```
// receive a message from bb
receive(bb):
    acquire(bb.lock)
    while bb.out >= bb.in:
        release(bb.lock)
        wait(bb.has_message)
        acquire(bb.lock)
    message <- bb.buf[bb.out mod N]
    bb.out <- bb.out + 1
    release(bb.lock)
    notify(bb.has_space)
    return message
```

question: what happens if `send()` is interrupted between lines 4 and 5?

`bb.has_space` = indicates that the buffer is not full (and so has space for at least one message)

`bb.has_message` = indicates that the buffer has at least one message in it

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// send a message by placing it in bb
1:  send(bb, message):
2:      acquire(bb.lock)
3:      while bb.in - bb.out >= N:
4:          release(bb.lock)
5:          wait(bb.has_space)
6:          acquire(bb.lock)
7:      bb.buf[bb.in mod N] <- message
8:      bb.in <- bb.in + 1
9:      release(bb.lock)
10:     notify(bb.has_message)
11:     return
```

```
// receive a message from bb
receive(bb):
    acquire(bb.lock)
    while bb.out >= bb.in:
        release(bb.lock)
        wait(bb.has_message)
        acquire(bb.lock)
    message <- bb.buf[bb.out mod N]
    bb.out <- bb.out + 1
    release(bb.lock)
    notify(bb.has_space)
    return message
```

problem: lost notify

bb.has_space = indicates that the buffer is not full (and so has space for at least one message)

bb.has_message = indicates that the buffer has at least one message in it

condition variables let threads wait for events (“conditions”), and get notified when they occur. can **wait** on a condition, and be **notified** of it occurring

```
// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        wait(bb.has_space, bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    notify(bb.has_message)
    return
```

condition variable API:

wait(cv, lock): yield processor, release lock, wait to be notified of cv

notify(cv): notify waiting threads of cv

bb.has_space = indicates that the buffer is not full (and so has space for at least one message)

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condition variables let threads wait for events (“conditions”), and get notified when they occur. can **wait** on a condition, and be **notified** of it occurring

```
// send a message by placing it in bb
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out >= N:
        wait(bb.has_space, bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    notify(bb.has_message)
    return
```

condition variable API:

`wait(cv, lock)`: yield processor, release lock, wait to be notified of cv

`notify(cv)`: notify waiting threads of cv

our second job today is to understand how **wait()** and **notify()** work, and also where **yield()** ends up in all of this

`bb.has_space` = indicates that the buffer is not full (and so has space for at least one message)

`bb.has_message` = indicates that the buffer has at least one message in it

`t_lock` makes `yield()` an atomic action

`threads` is a table that contains information about each of the current threads

for each thread it stores the thread's

- state: RUNNABLE, RUNNING
- stack pointer (sp)
- page table register (ptr)

`cpus` is a table that keeps track of the id of the thread currently running on each cpu

SP = current stack pointer

PTR = current page table register

CPU = current cpu

wait(cv, lock) releases lock, sets the current thread to be waiting on cv, yields, and then re-acquires lock

t_lock makes **yield()** and **wait()** atomic actions

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cpus is a table that keeps track of the id of the thread currently running on each cpu

SP = current stack pointer

PTR = current page table register

CPU = current cpu

```
wait(cv, lock):
    acquire(t_lock)
    // release lock

    // set current thread to be
    // waiting on cv

    // yield

    release(t_lock)
    // re-acquire lock
```

wait(cv, lock) releases lock, sets the current thread to be waiting on cv, yields, and then re-acquires lock

t_lock makes **yield()** and **wait()** atomic actions

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CPU = current cpu

```
wait(cv, lock):  
    acquire(t_lock)  
    release(lock)
```

```
// set current thread to be  
// waiting on cv
```

```
// yield
```

```
release(t_lock)  
acquire(lock)
```

wait(cv, lock) releases lock, sets the current thread to be waiting on cv, yields, and then re-acquires lock

t_lock makes **yield()** and **wait()** atomic actions

threads is a table that contains information about each of the current threads

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- state: RUNNABLE, RUNNING, WAITING
- stack pointer (sp)
- page table register (ptr)
- condition to be notified of (cv)

cpus is a table that keeps track of the id of the thread currently running on each cpu

SP = current stack pointer

PTR = current page table register

CPU = current cpu

```
wait(cv, lock):
    acquire(t_lock)
    release(lock)

    id = cpus[CPU].thread
    threads[id].cv = cv
    threads[id].state = WAITING

    // yield

    release(t_lock)
    acquire(lock)
```

wait(cv, lock) releases lock, sets the current thread to be waiting on cv, yields, and then re-acquires lock

t_lock makes **yield()** and **wait()** atomic actions

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cpus is a table that keeps track of the id of the thread currently running on each cpu

SP = current stack pointer

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CPU = current cpu

```
wait(cv, lock):  
    acquire(t_lock)  
    release(lock)
```

```
id = cpus[CPU].thread  
threads[id].cv = cv  
threads[id].state = WAITING
```

```
yield_wait()
```

```
release(t_lock)  
acquire(lock)
```

wait(cv, lock) releases lock, sets the current thread to be waiting on cv, yields, and then re-acquires lock

t_lock makes **yield()** and **wait()** atomic actions

threads is a table that contains information about each of the current threads

for each thread it stores the thread's

- state: RUNNABLE, RUNNING, WAITING
- stack pointer (sp)
- page table register (ptr)
- condition to be notified of (cv)

cpus is a table that keeps track of the id of the thread currently running on each cpu

SP = current stack pointer

PTR = current page table register

CPU = current cpu

```
wait(cv, lock):  
    acquire(t_lock)  
    release(lock)
```

```
id = cpus[CPU].thread  
threads[id].cv = cv  
threads[id].state = WAITING
```

```
yield_wait()
```

```
release(t_lock)  
acquire(lock)
```

for right now, you can assume that **yield_wait()** is the same as **yield()**

we're giving it a different name, because we're going to find that it needs to be a slightly different function

condition variables let threads wait for events (“conditions”), and get notified when they occur
can **wait** on a condition, and be **notified** of it occurring

```
notify(cv):  
    acquire(t_lock)  
    for id = 0 to N-1:  
        if threads[id].cv == cv &&  
            threads[id].state == WAITING:  
            threads[id].state = RUNNABLE  
    release(t_lock)
```

notify(cv) finds all threads waiting on cv, and sets
their state to RUNNABLE (i.e., ready to be run; *not*
RUNNING)

```
wait(cv, lock):  
    acquire(t_lock)  
    release(lock)  
    id = cpus[CPU].thread  
    threads[id].cv = cv  
    threads[id].state = WAITING  
    yield_wait()  
    release(t_lock)  
    acquire(lock)
```

we’re going to get back to `yield_wait()` in a second, but
just for context, here’s how `notify()` works

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    acquire(lock)
```

```
yield_wait():
    acquire(t_lock)

    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].state = RUNNABLE
    threads[id].sp = SP
    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
    while threads[id].state != RUNNABLE

    // Resume the new thread
    SP = threads[id].sp
    PTR = threads[id].ptr
    threads[id].state = RUNNING
    cpus[CPU].thread = id

    release(t_lock)
```

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    threads[id].cv = cv
    threads[id].state = WAITING
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    acquire(lock)
```

problem: **wait()** holds **t_lock**

```
yield_wait():
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    // Suspend the running thread
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    threads[id].cv = cv
    threads[id].state = WAITING
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    release(t_lock)
    acquire(lock)
```

problem: current thread's state
shouldn't be set to **RUNNABLE**
(**wait()** has already set it to **WAITING**)

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yield_wait():
    // Suspend the running thread
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    threads[id].ptr = PTR

    // Choose a new thread to run
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    release(t_lock)
    acquire(lock)
```

problem: deadlock

(**wait()** holds **t_lock**, but **notify()** also needs it)

```
yield_wait():
    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].sp = SP
    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
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    acquire(lock)
```

problem: stack corruption

```
yield_wait():
    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].sp = SP
    threads[id].ptr = PTR

    // Choose a new thread to run
    do:
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        release(t_lock)
        acquire(t_lock)
    while threads[id].state != RUNNABLE

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    threads[id].cv = cv
    threads[id].state = WAITING
    yield_wait()
    release(t_lock)
    acquire(lock)
```

```
yield_wait():
    // Suspend the running thread
    id = cpus[CPU].thread
    threads[id].sp = SP
    threads[id].ptr = PTR
    SP = cpus[CPU].stack

    // Choose a new thread to run
    do:
        id = (id + 1) mod N
        release(t_lock)
        acquire(t_lock)
    while threads[id].state != RUNNABLE

    // Resume the new thread
    SP = threads[id].sp
    PTR = threads[id].ptr
    threads[id].state = RUNNING
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```

we've done so much work. but what if threads just never call `wait()` (or `yield()`)?

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    push PC  
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```

notice the need for some assistance from hardware here! just like how we required an atomic exchange operation for locks, and how we require the physical addresses of the page table registers for virtual memory to work

(and also similar to how the IP addresses of the DNS root servers are hardcoded into clients)

choosing a new thread to run is the problem of **scheduling**

```
yield():  
    acquire(t_lock)  
  
    // Suspend the running thread  
    id = cpus[CPU].thread  
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    threads[id].sp = SP  
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    // Choose a new thread to run  
    do:  
        id = (id + 1) mod N  
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how threads are scheduled has a large **impact** on performance and **fairness**; there is no *best* scheduling algorithm

operating systems enforce modularity on a single machine

in order to enforce modularity + have an effective operating system, a few things need to happen

- | | | |
|---|--------|---|
| 1. programs shouldn't be able to refer to
(and corrupt) each others' memory |→ | virtualize memory |
| 2. programs should be able to
communicate with each other |→ | bounded buffers
(virtualize communication links) |
| 3. programs should be able to share a CPU without one program halting the progress of the others |→ | threads
(virtualize processors) |

threads virtualize a processor so that we can share it among programs. **yield()** allows the kernel to suspend the current thread and resume another

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condition variables provide a more efficient API for threads, where they **wait** for an event and are **notified** when it occurs. **wait()** requires a new version of **yield()**, **yield_wait()**

preemption forces a thread to be interrupted so that the kernel doesn't have to rely on programmers correctly using **yield()**. requires a special **interrupt** and hardware support to disable other interrupts