Understanding the Python GIL

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Introduction

- As a few of you might know, C Python has a Global Interpreter Lock (GIL)

```
>>> import that
The Unwritten Rules of Python

1. You do not talk about the GIL.
2. You do NOT talk about the GIL.
3. Don't even mention the GIL. No seriously.
...
```

- It limits thread performance
- Thus, a source of occasional "contention"

An Experiment

- Consider this trivial CPU-bound function

```
def countdown(n):
    while n > 0:
        n -= 1
```

- Run it once with a lot of work

```
COUNT = 100000000   # 100 million
countdown(COUNT)
```

- Now, subdivide the work across two threads

```
t1 = Thread(target=countdown,args=(COUNT//2,))
t2 = Thread(target=countdown,args=(COUNT//2,))
t1.start(); t2.start()
t1.join(); t2.join()
```

A Mystery

- Performance on a quad-core MacPro

Sequential	: 7.8s	
Threaded (2 threads)	: 15.4s	(2X slower!)

- Performance if work divided across 4 threads

Threaded (4 threads)	: 15.7s	(about the same)

- Performance if all but one CPU is disabled

Threaded (2 threads)	: 11.3s	(~35% faster than running
Threaded (4 threads)	: 11.6s	with all 4 cores)

- Think about it...

This Talk

- An in-depth look at threads and the GIL that will explain that mystery and much more
- Some cool pictures
- A look at the new GIL in Python 3.2

Disclaimers

- I gave an earlier talk on this topic at the Chicago Python Users Group (chipy)

  http://www.dabeaz.com/python/GIL.pdf

- That is a different, but related talk
- I'm going to go pretty fast... please hang on

Part I

Threads and the GIL

Python Threads

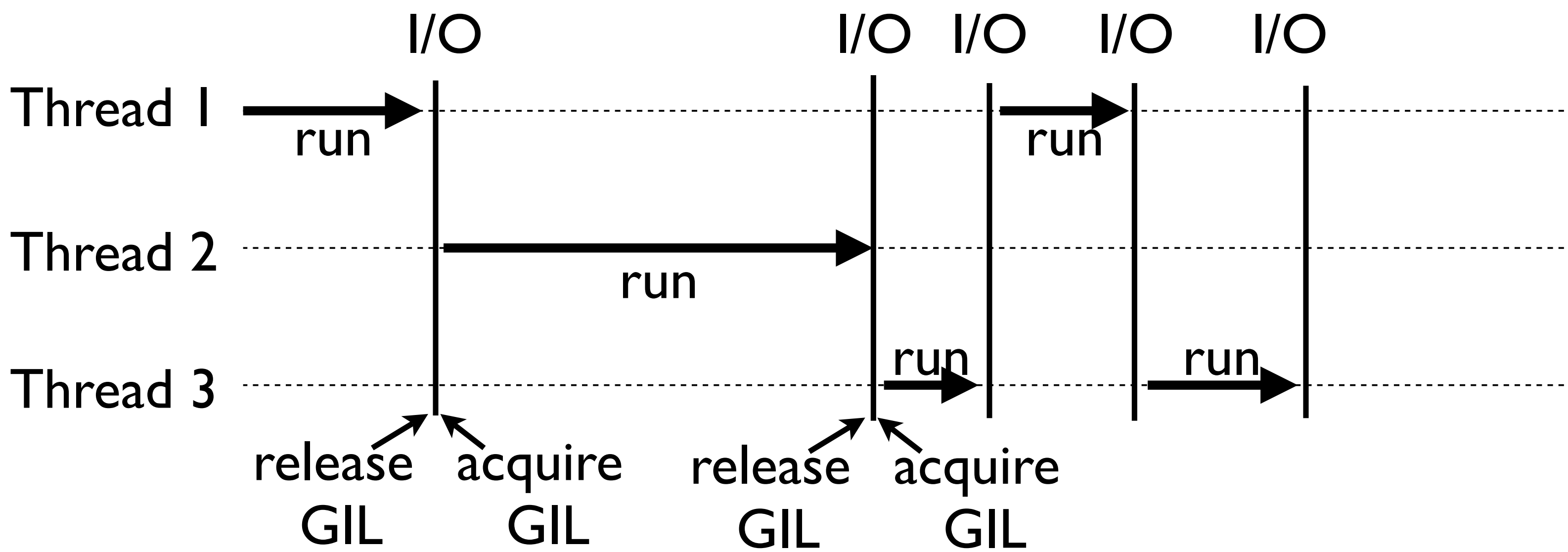
- Python threads are real system threads
    - POSIX threads (pthreads)
    - Windows threads
- Fully managed by the host operating system
- Represent threaded execution of the Python interpreter process (written in C)

Alas, the GIL

- Parallel execution is forbidden
- There is a "global interpreter lock"
- The GIL ensures that only one thread runs in the interpreter at once
- Simplifies many low-level details (memory management, callouts to C extensions, etc.)

Thread Execution Model

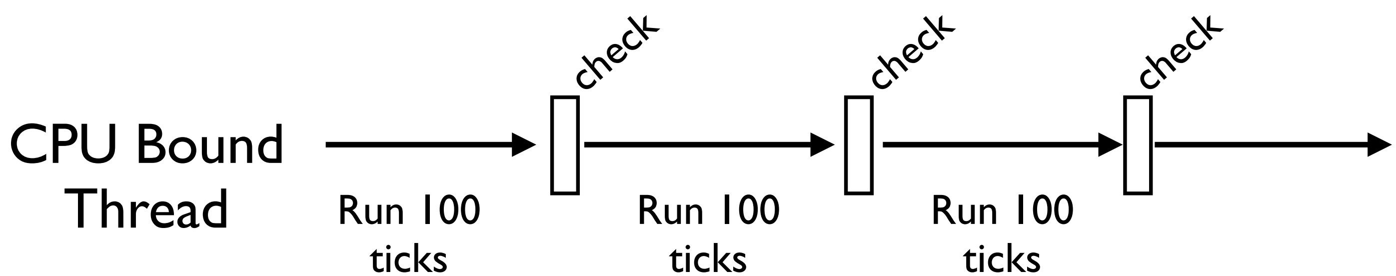
- With the GIL, you get cooperative multitasking



- When a thread is running, it holds the GIL
- GIL released on I/O (read,write,send,recv,etc.)

CPU Bound Tasks

- CPU-bound threads that never perform I/O are handled as a special case
- A "check" occurs every 100 "ticks"



- Change it using sys.setcheckinterval()

What is a "Tick?"

- Ticks <u>loosely</u> map to interpreter instructions

```
def countdown(n):
    while n > 0:
        print n
        n -= 1
```

- Instructions in the Python VM
- Not related to timing (ticks might be long)

```
>>> import dis
>>> dis.dis(countdown)
          0 SETUP_LOOP              33 (to 36)
          3 LOAD_FAST                0 (n)
          6 LOAD_CONST               1 (0)
          9 COMPARE_OP               4 (>)
Tick 1   12 JUMP_IF_FALSE           19 (to 34)
         15 POP_TOP
         16 LOAD_FAST                0 (n)
         19 PRINT_ITEM
Tick 2   20 PRINT_NEWLINE
         21 LOAD_FAST                0 (n)
Tick 3   24 LOAD_CONST               2 (1)
         27 INPLACE_SUBTRACT
         28 STORE_FAST               0 (n)
Tick 4   31 JUMP_ABSOLUTE            3
         ...
```

The Periodic "Check"

- The periodic check is really simple
- The currently running thread...
  - Resets the tick counter
  - Runs signal handlers if the main thread
  - Releases the GIL
  - Reacquires the GIL
- That's it

Implementation (C)

Note: Each thread is running this same code

Decrement ticks

```
/* Python/ceval.c */
...
if (--_Py_Ticker < 0) {
    ...
```

Reset ticks

```
    _Py_Ticker = _Py_CheckInterval;
    ...
```

Run signal handlers

```
    if (things_to_do) {
        if (Py_MakePendingCalls() < 0) {
            ...
        }
    }
```

Release and reacquire the GIL

```
    if (interpreter_lock) {
        /* Give another thread a chance */
        PyThread_release_lock(interpreter_lock);

        /* Other threads may run now */

        PyThread_acquire_lock(interpreter_lock, 1);
    }
...
```

Big Question

- What is the source of that large CPU-bound thread performance penalty?
- There's just not much code to look at
- Is GIL acquire/release solely responsible?
- How would you find out?

Part 2

The GIL and Thread Switching Deconstructed

Python Locks

- The Python interpreter only provides a <u>single</u> lock type (in C) that is used to build all other thread synchronization primitives
- It's <u>not</u> a simple mutex lock
- It's a binary semaphore constructed from a pthreads mutex and a condition variable
- The GIL is an instance of this lock

Locks Deconstructed

- Locks consist of three parts

```
locked = 0                   # Lock status
mutex  = pthreads_mutex()    # Lock for the status
cond   = pthreads_cond()     # Used for waiting/wakeup
```

- Here's how acquire() and release() work

pseudocode

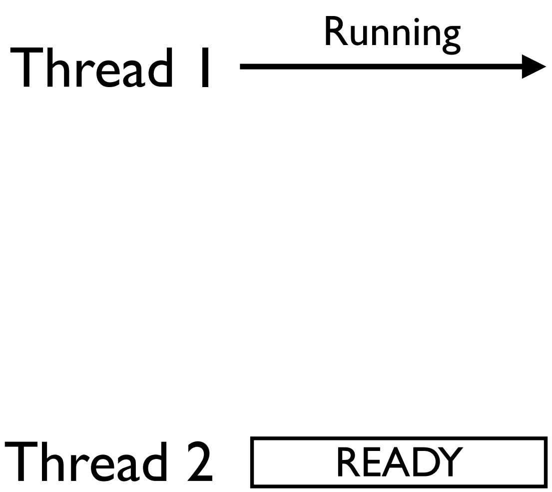
```
release() {
    mutex.acquire()
    locked = 0
    mutex.release()
    cond.signal()
}
```

```
acquire() {
    mutex.acquire()
    while (locked) {
        cond.wait(mutex)
    }
    locked = 1
    mutex.release()
}
```

A critical aspect concerns this signaling between threads

Thread Switching

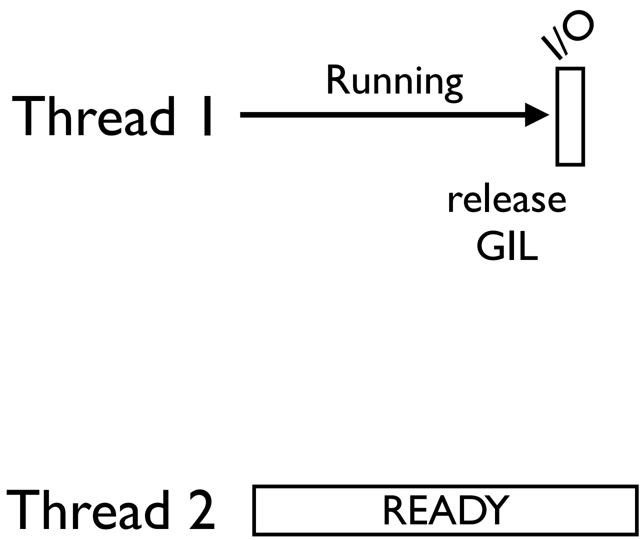
- Suppose you have two threads



- Thread 1 : Running
- Thread 2 : Ready (Waiting for GIL)

Thread Switching

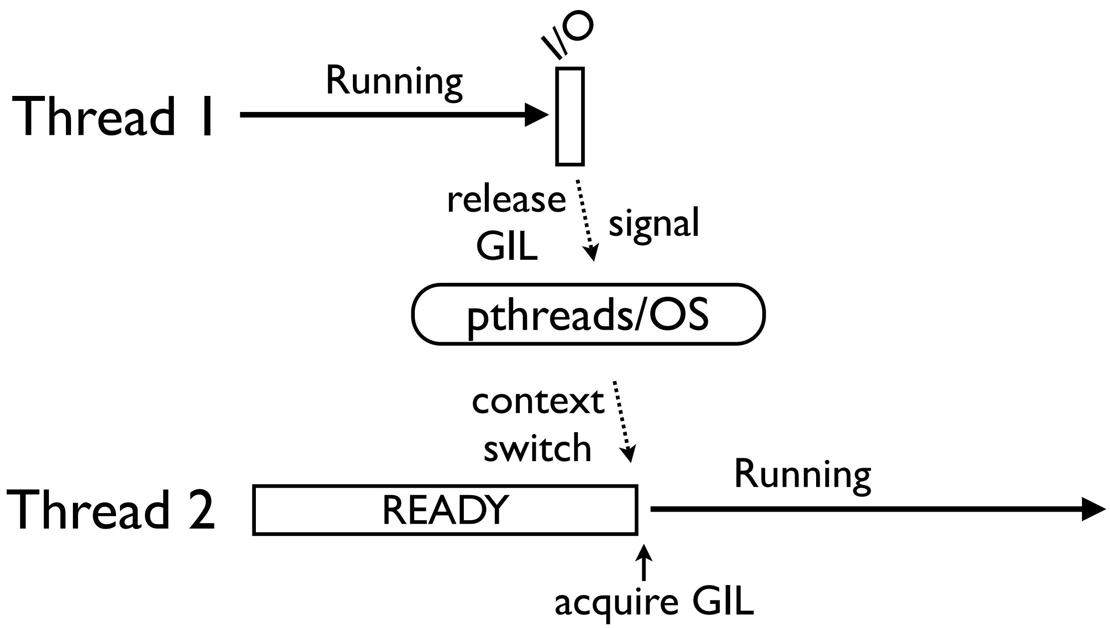
- Easy case : Thread 1 performs I/O (read/write)



- Thread 1 might block so it releases the GIL

Thread Switching

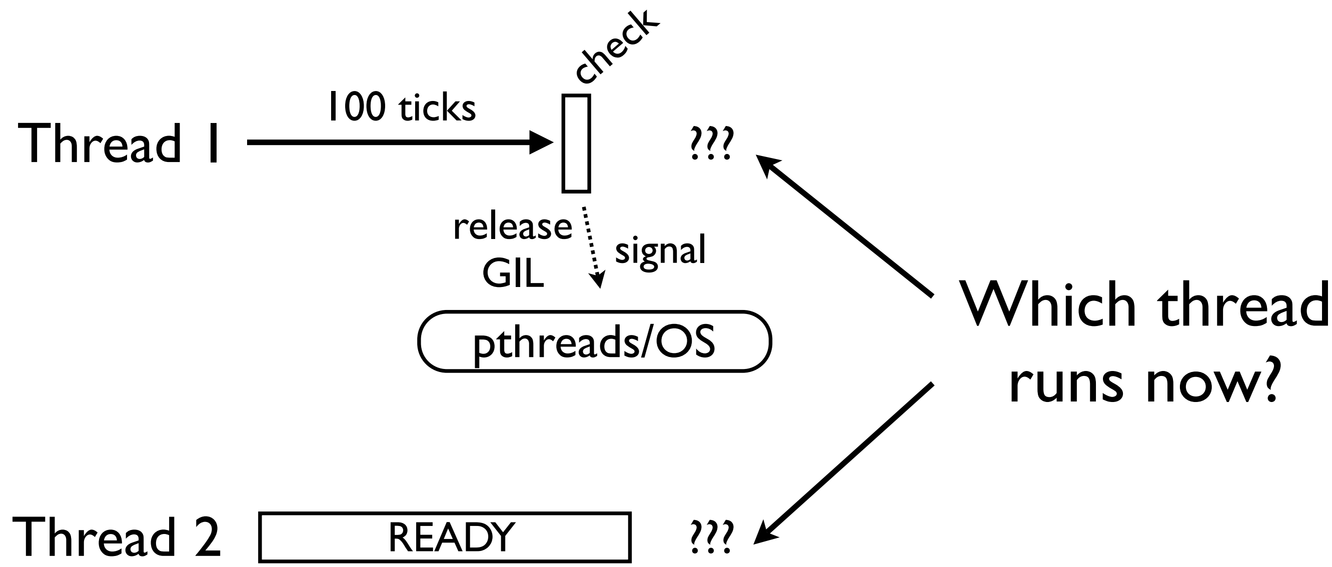
- Easy case : Thread 1 performs I/O (read/write)



- Release of GIL results in a signaling operation
- Handled by thread library and operating system

Thread Switching

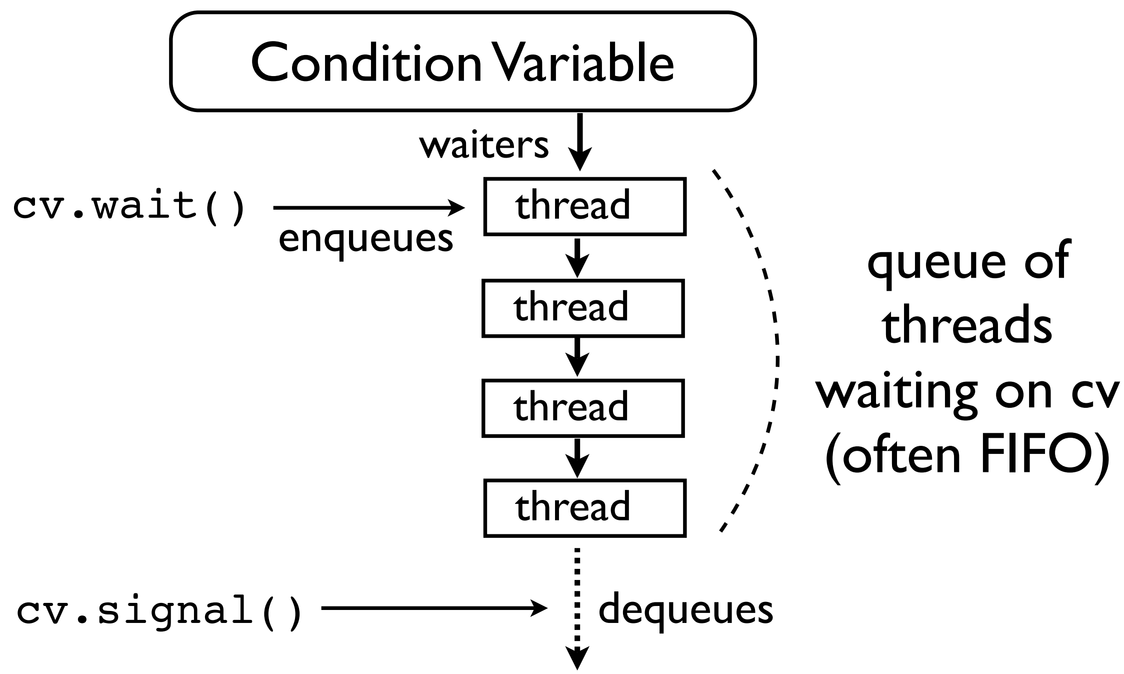
- Tricky case : Thread 1 runs until the check



- Either thread is able to run
- So, which is it?

pthreads Undercover

- Condition variables have an internal wait queue



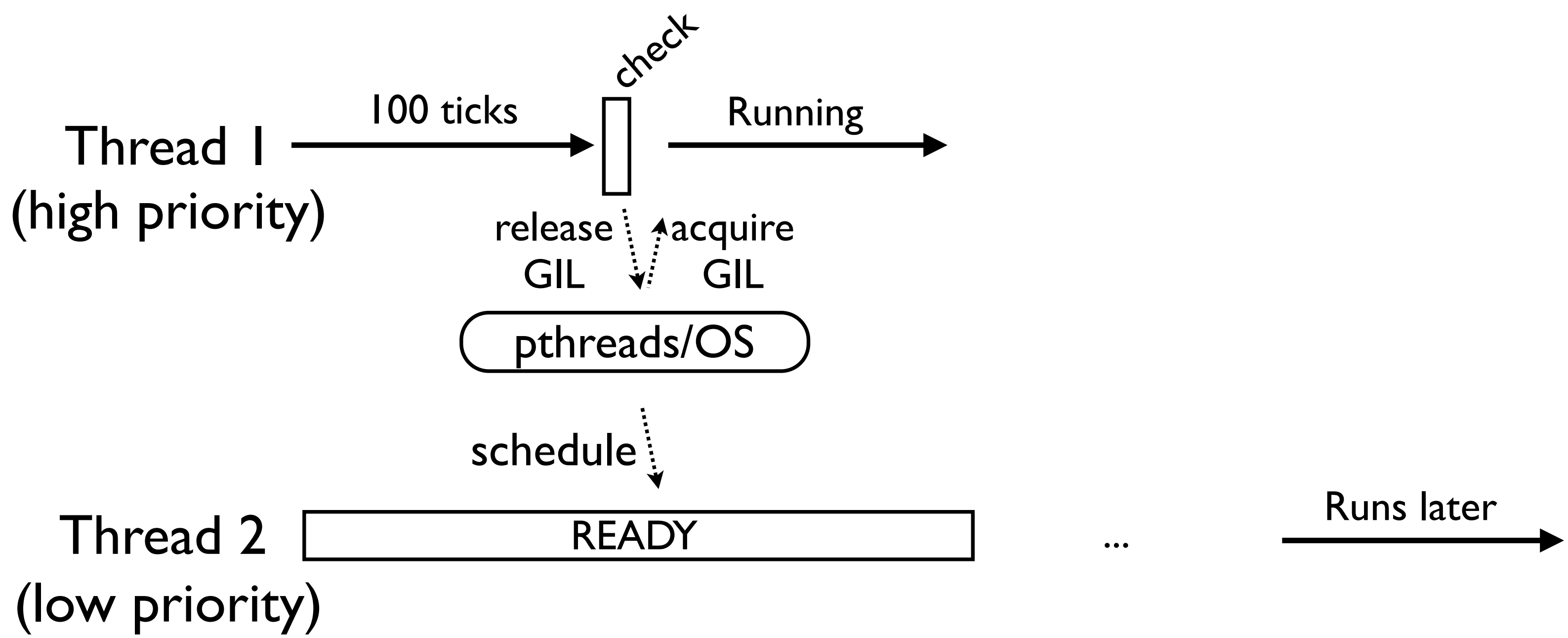
- Signaling pops a thread off of the queue
- However, what happens after that?

OS Scheduling

- The operating system has a priority queue of threads/processes ready to run
- Signaled threads simply enter that queue
- The operating system then runs the process or thread with the highest priority
- It may or may not be the signaled thread

Thread Switching

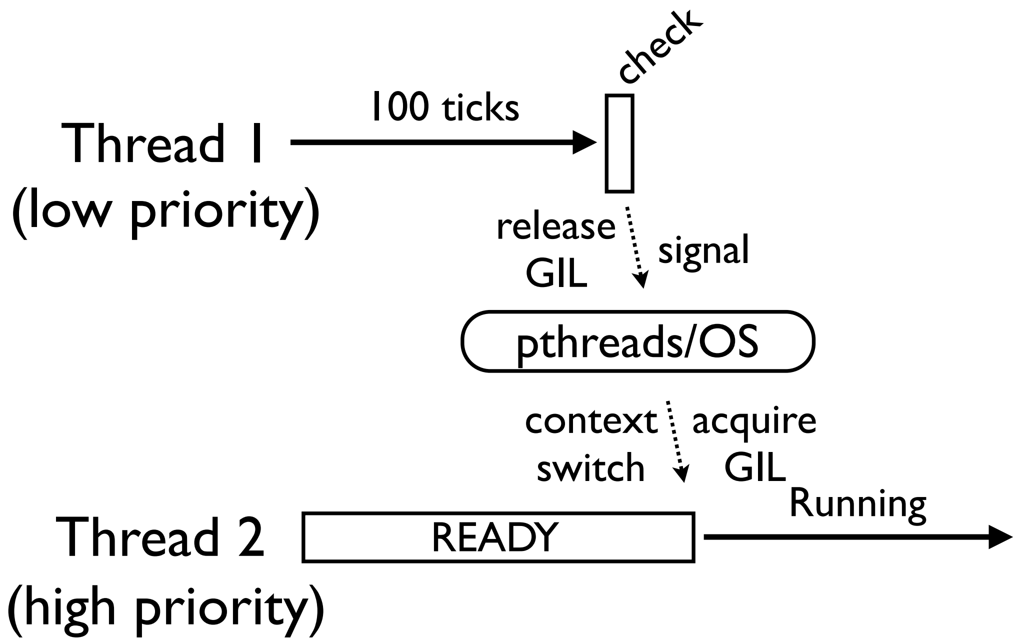
- Thread 1 might keep going



- Thread 2 moves to the OS "ready" queue and executes at some later time

Thread Switching

- Thread 2 might immediately take over



- Again, highest priority wins

Part 3

What Can Go Wrong?

GIL Instrumentation

- To study thread scheduling in more detail, I instrumented Python with some logging
- Recorded a large trace of all GIL acquisitions, releases, conflicts, retries, etc.
- Goal was to get a better idea of how threads were scheduled, interactions between threads, internal GIL behavior, etc.

GIL Logging

- An extra tick counter was added to record number of cycles of the check interval
- Locks modified to log GIL events (pseudocode)

```
release() {
    mutex.acquire()
    locked = 0
    if gil: log("RELEASE")
    mutex.release()
    cv.signal()
}
```

```
acquire() {
    mutex.acquire()
    if locked and gil:
        log("BUSY")
    while locked:
        cv.wait(mutex)
        if locked and gil:
            log("RETRY")
    locked = 1
    if gil: log("ACQUIRE")
    mutex.release()
}
```

Note: Actual code in C, event logs are stored entirely in memory until exit (no I/O)

A Sample Trace

thread id

tick countdown

total number of "checks" executed

```
t2 100 5351 ACQUIRE
t2 100 5352 RELEASE
t2 100 5352 ACQUIRE
t2 100 5353 RELEASE
t1 100 5353 ACQUIRE
t2  38 5353 BUSY
t1 100 5354 RELEASE
t1 100 5354 ACQUIRE
t2  79 5354 RETRY
t1 100 5355 RELEASE
t1 100 5355 ACQUIRE
t2  73 5355 RETRY
t1 100 5356 RELEASE
t2 100 5356 ACQUIRE
t1  24 5356 BUSY
t2 100 5357 RELEASE
```

ACQUIRE : GIL acquired

RELEASE : GIL released

BUSY : Attempted to acquire GIL, but it was already in use

RETRY : Repeated attempt to acquire the GIL, but it was still in use

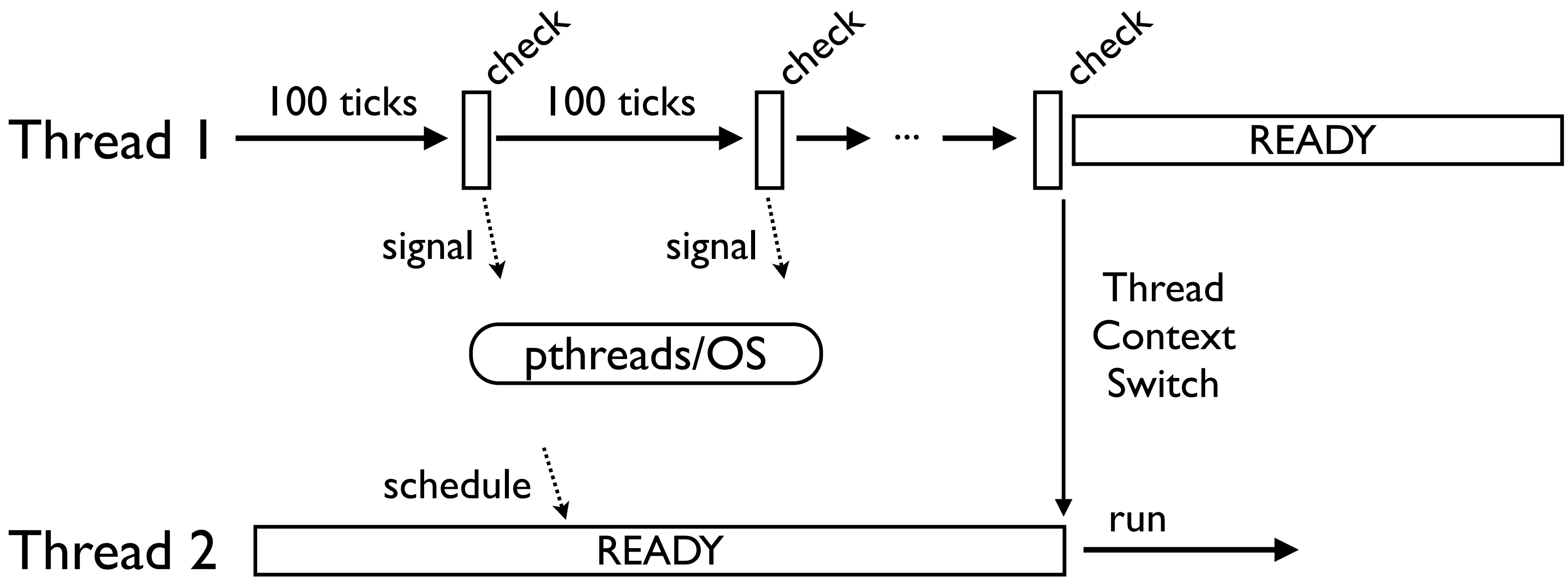
- Trace files were large (>20MB for 1s of running)

Logging Results

- The logs were <u>quite</u> revealing
- Interesting behavior on one CPU
- Diabolical behavior on multiple CPUs
- Will briefly summarize findings followed by an interactive visualization that shows details

Single CPU Threading

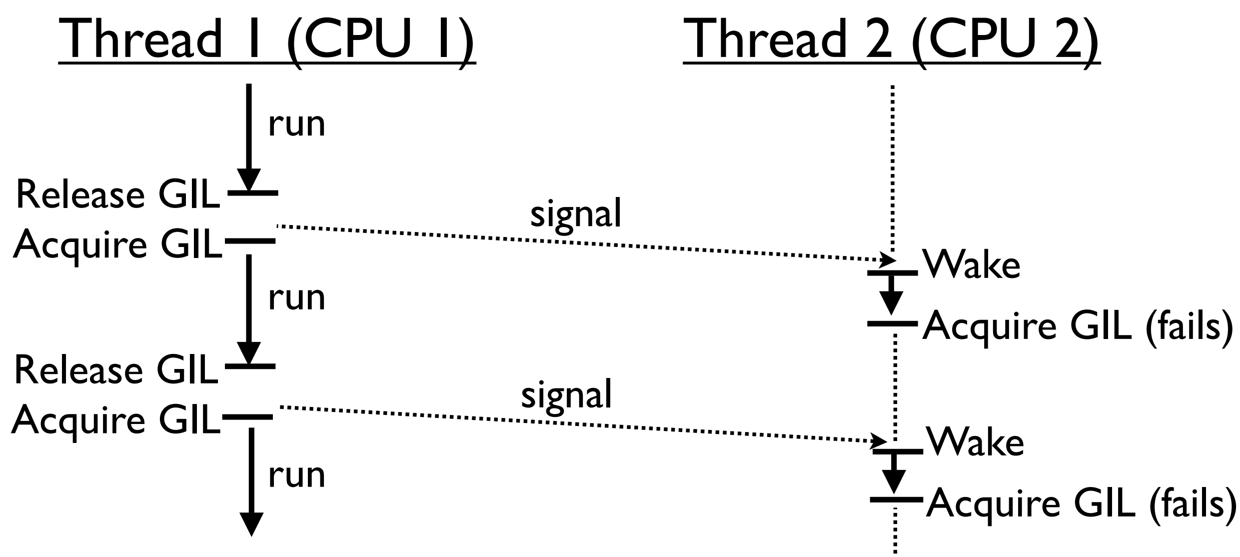
- Threads alternate execution, but switch far less frequently than you might imagine



- Hundreds to thousands of checks might occur before a thread context switch (this is good)

Multicore GIL War

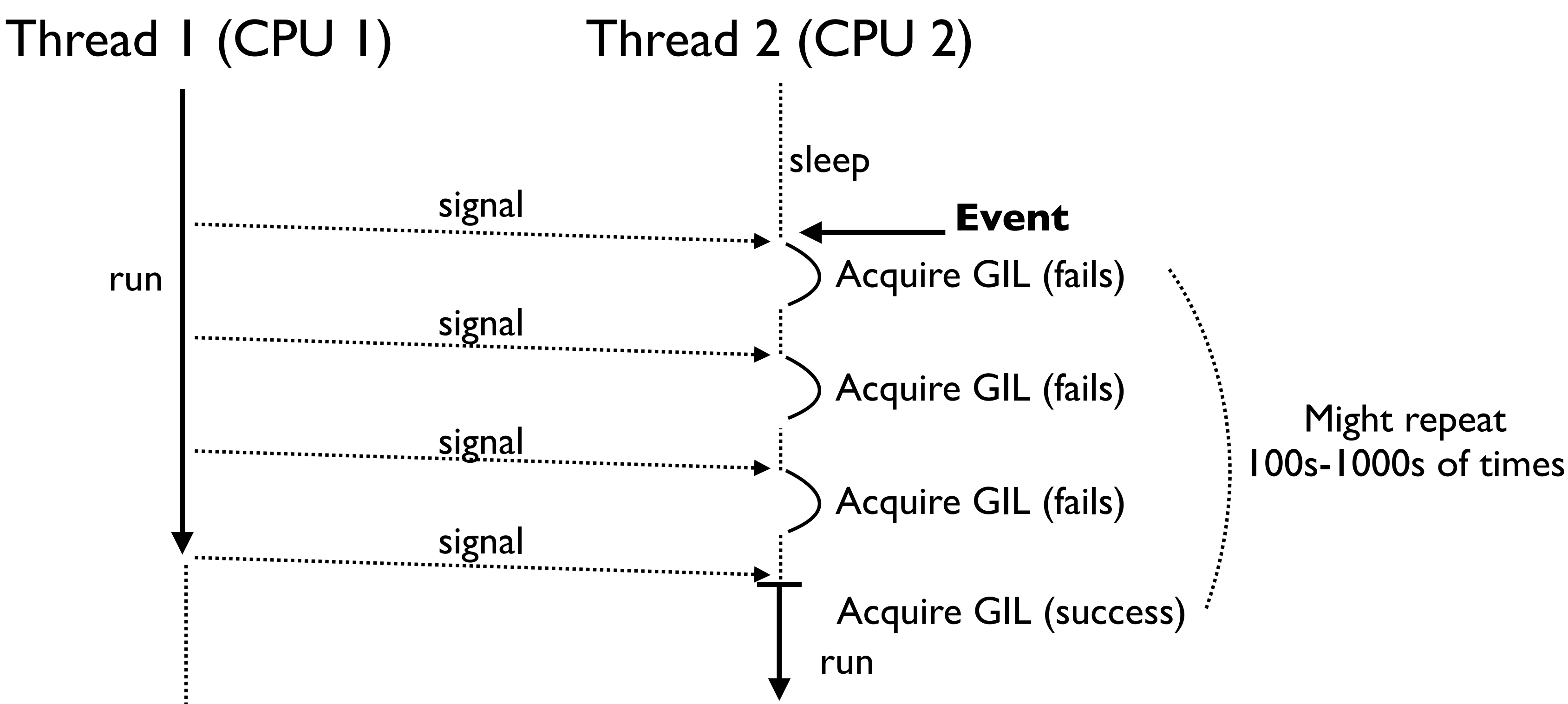
- With multiple cores, runnable threads get scheduled <u>simultaneously</u> (on different cores) and battle over the GIL



- Thread 2 is repeatedly signaled, but when it wakes up, the GIL is already gone (reacquired)

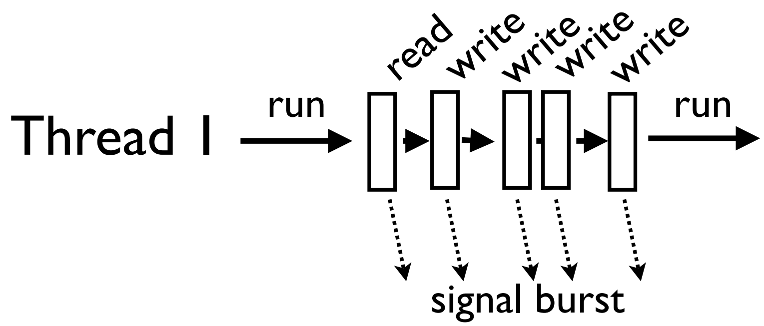
Multicore Event Handling

- CPU-bound threads make GIL acquisition difficult for threads that want to handle events



Behavior of I/O Handling

- I/O ops often <u>do not block</u>



- Due to buffering, the OS is able to fulfill I/O requests immediately and keep a thread running
- However, the GIL is always released
- Results in GIL thrashing under heavy load

GIL Visualization (Demo)

- Let's look at all of these effects

http://www.dabeaz.com/GIL

- Some facts about the plots:
  - Generated from ~2GB of log data
  - Rendered into ~2 million PNG image tiles
  - Created using custom scripts/tools
  - I used the multiprocessing module

Part 4

A Better GIL?

The New GIL

- Python 3.2 has a new GIL implementation (only available by svn checkout)
- The work of Antoine Pitrou (applause)
- It aims to solve all that GIL thrashing
- It is the first major change to the GIL since the inception of Python threads in 1992
- Let's go take a look

New Thread Switching

- Instead of ticks, there is now a global variable

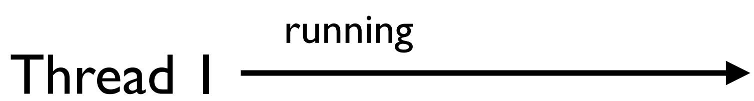
```
/* Python/ceval.c */
...

static volatile int gil_drop_request = 0;
```

- A thread runs until the value gets set to 1
- At which point, the thread <u>must</u> drop the GIL
- Big question: How does that happen?

New GIL Illustrated

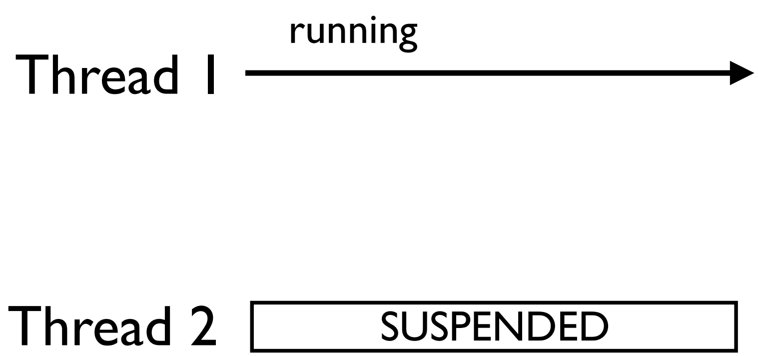
- Suppose that there is just one thread



- It just runs and runs and runs ...
  - Never releases the GIL
  - Never sends any signals
  - Life is great!

New GIL Illustrated

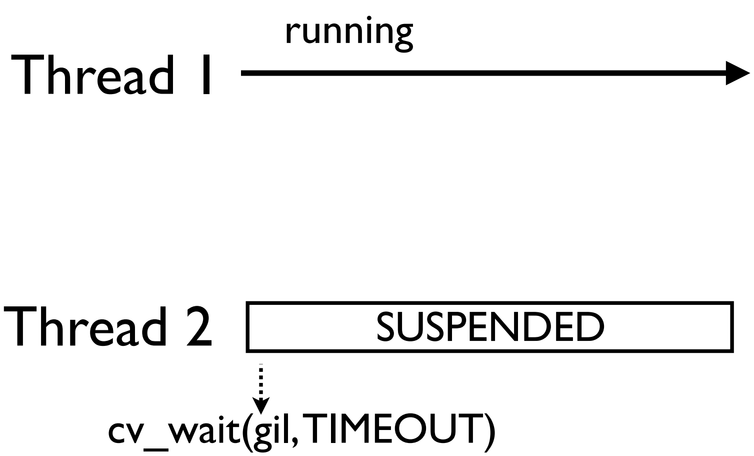
- Suppose, a second thread appears



- It is suspended because it doesn't have the GIL
- Somehow, it has to get it from Thread 1

New GIL Illustrated

- Waiting thread does a timed cv_wait on GIL

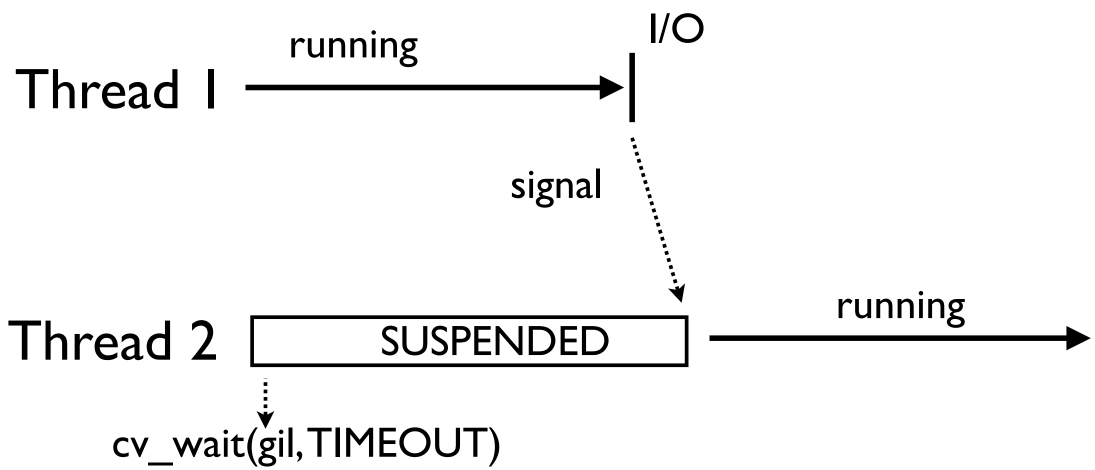


By default TIMEOUT is 5 milliseconds, but it can be changed

- The idea : Thread 2 waits to see if the GIL gets released voluntarily by Thread 1 (e.g., if there is I/O or it goes to sleep for some reason)

New GIL Illustrated

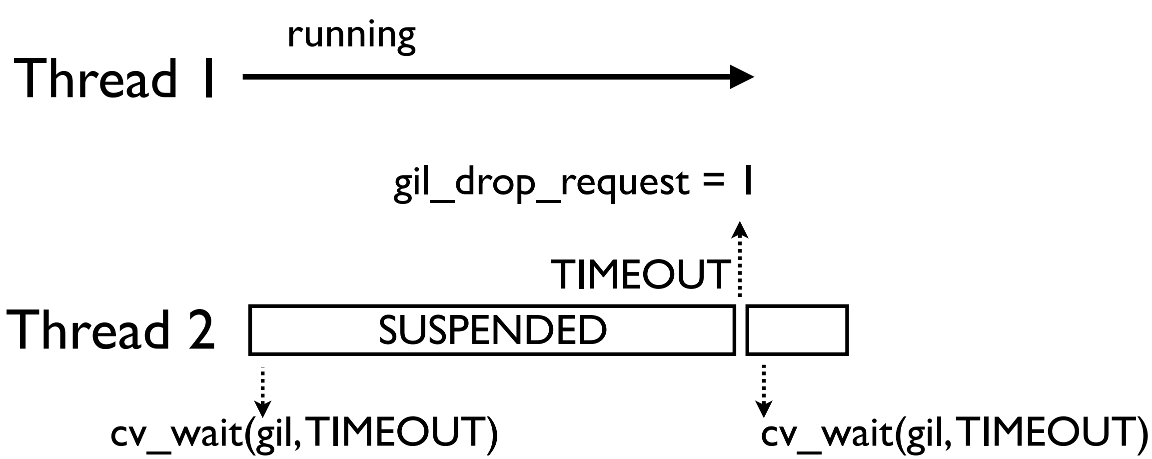
- Voluntary GIL release



- This is the easy case. Second thread is signaled and it grabs the GIL.

New GIL Illustrated

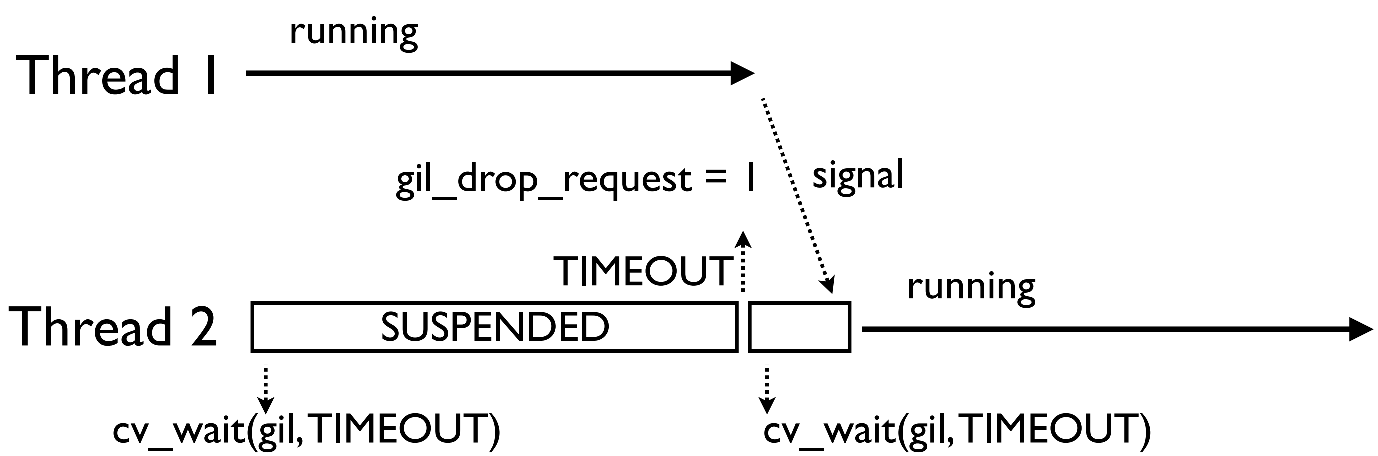
- If timeout, set gil_drop_request



- Thread 2 then repeats its wait on the GIL

New GIL Illustrated

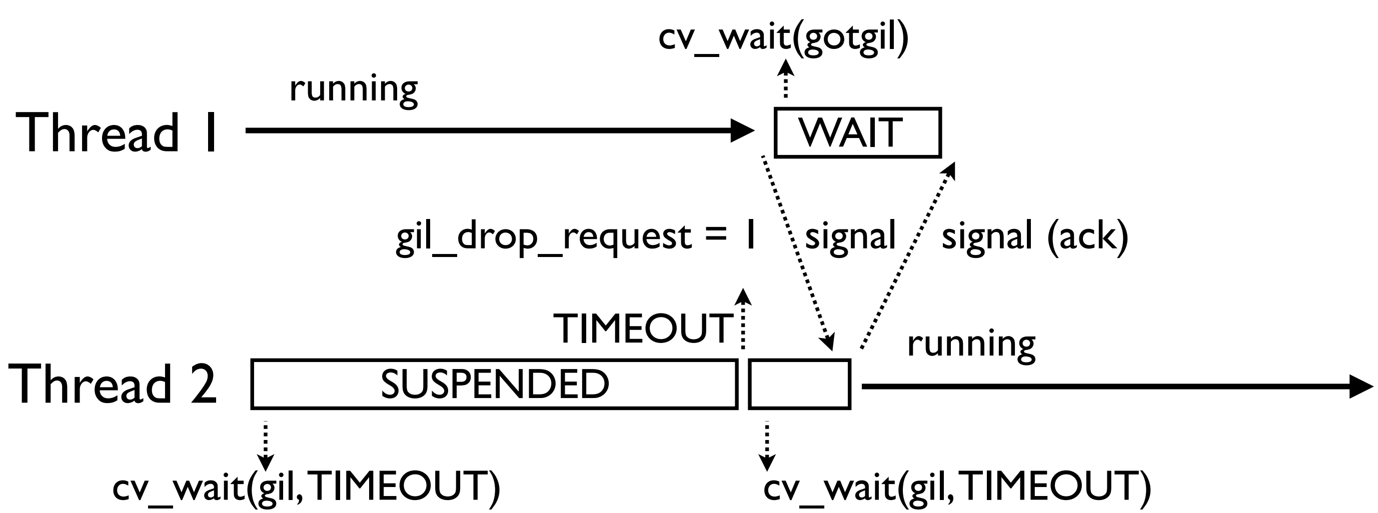
- Thread 1 suspends after current instruction



- Signal is sent to indicate release of GIL

New GIL Illustrated

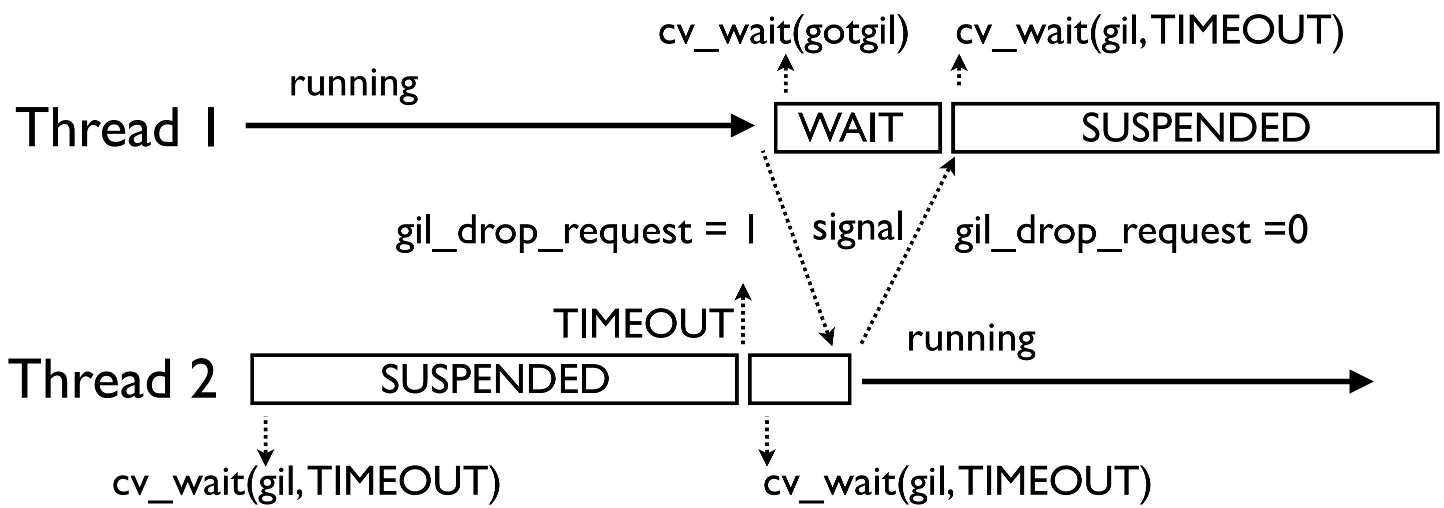
- On a forced release, a thread waits for an ack



- Ack ensures that the other thread successfully got the GIL and is now running
- This eliminates the "GIL Battle"

New GIL Illustrated

- The process now repeats itself for Thread 1



- So, the timeout sequence happens over and over again as CPU-bound threads execute

Does it Work?

- Yes, apparently (4-core MacPro, OS-X 10.6.2)

Sequential		: 11.53s
Threaded	(2 threads)	: 11.93s
Threaded	(4 threads)	: 12.32s

- Keep in mind, Python is still limited by the GIL in all of the usual ways (threads still provide no performance boost)
- But, otherwise, it looks promising!

Part 5

Die GIL Die!!!

Alas, It Doesn't Work

- The New GIL impacts I/O performance
- Here is a fragment of network code

Thread 1

```
def spin():
    while True:
        # some work
        pass
```

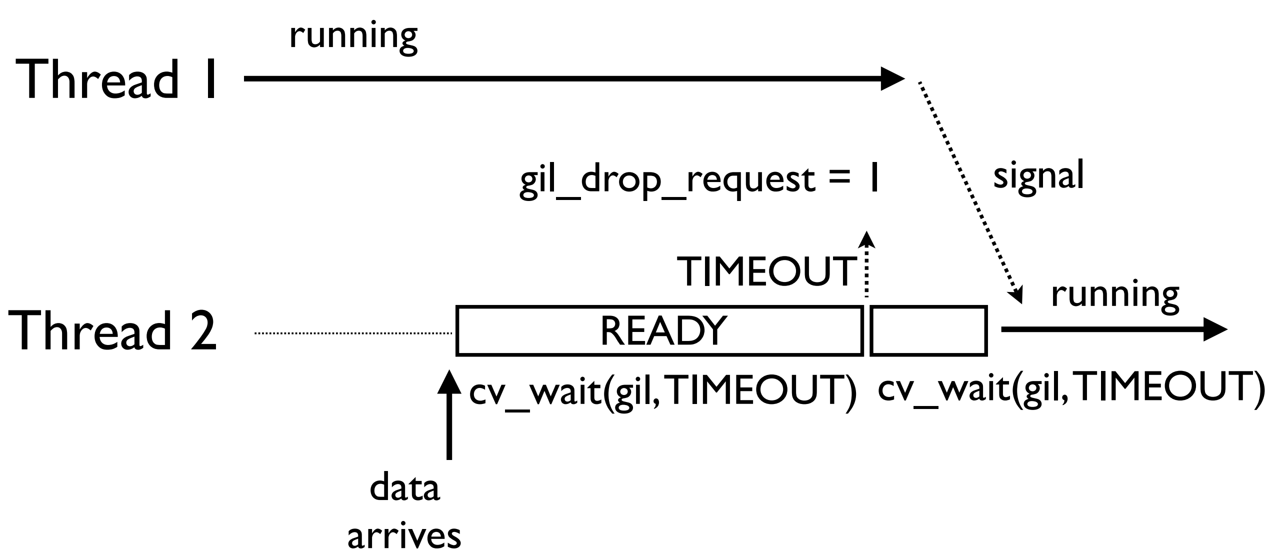
Thread 2

```
def echo_server(s):
    while True:
        data = s.recv(8192)
        if not data:
            break
        s.sendall(data)
```

- One thread is working (CPU-bound)
- One thread receives and echos data on a socket

Response Time

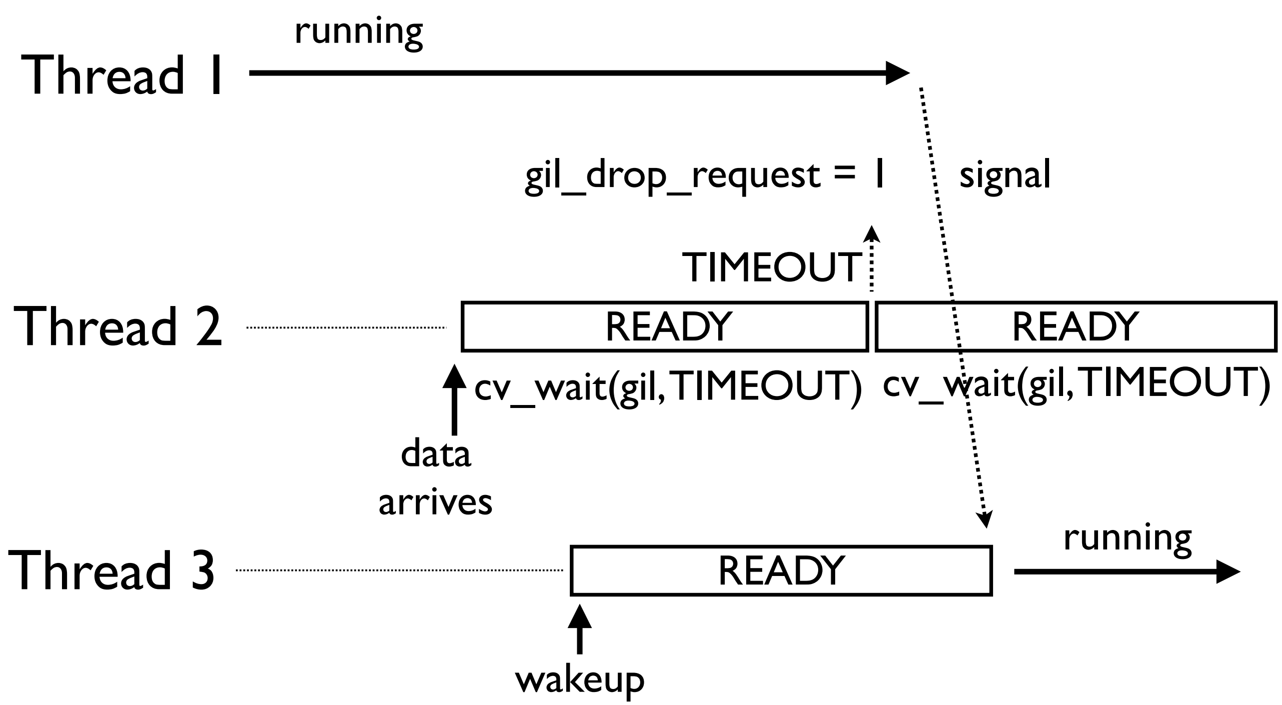
- New GIL increases response time



- To handle I/O, a thread must go through the entire timeout sequence to get control
- Ignores the high priority of I/O or events

Unfair Wakeup/Starvation

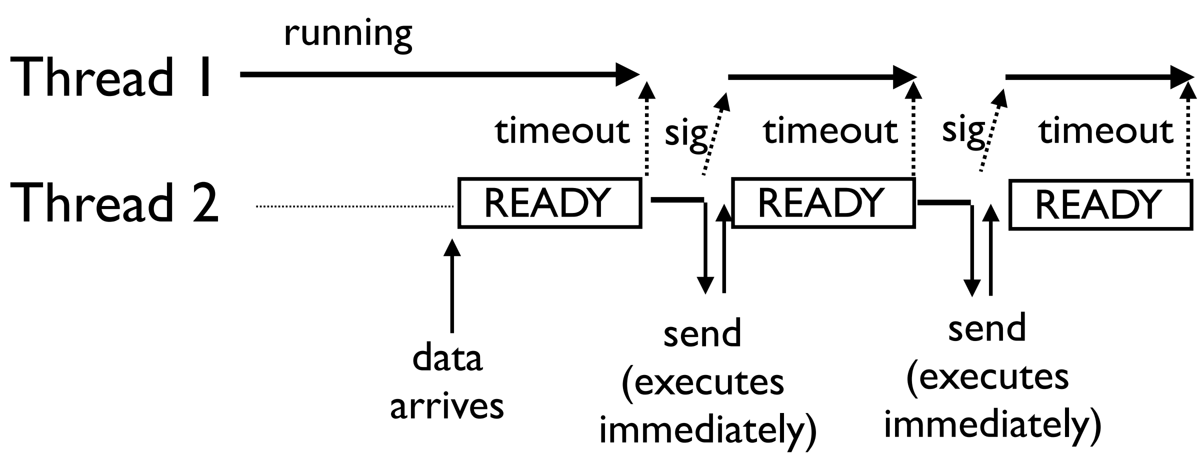
- Most deserving thread may not get the GIL



- Caused by internal condition variable queuing
- Further increases the response time

Convoy Effect

- I/O operations that don't block cause stalls



- Since I/O operations always release the GIL, CPU-bound threads will always try to restart
- On I/O completion (almost immediately), the GIL is gone so the timeout has to repeat

An Experiment

- Send 10MB of data to an echo server thread that's competing with a CPU-bound thread

  Python 2.6.4 (2 CPU) : 0.57s (10 sample average)
  Python 3.2 (2 CPU) : 12.4s (20x slower)

- What if echo competes with 2 CPU threads?

  Python 2.6.4 (2 CPU) : 0.25s (Better performance?)
  Python 3.2 (2 CPU) : 46.9s (4x slower than before)
  Python 3.2 (1 CPU) : 0.14s (330x faster than 2 cores?)

- Arg! Enough already!

Part 6

Score : Multicore 2, GIL 0

Fixing the GIL

- Can the GIL's erratic behavior be fixed?
- My opinion : Yes, maybe.
- The new GIL is already 90% there
- It just needs a few extra bits

The Missing Bits

- Priorities: There must be some way to separate CPU-bound (low priority) and I/O bound (high priority) threads
- Preemption: High priority threads must be able to immediately preempt low-priority threads

A Possible Solution

- Operating systems use timeouts to automatically adjust task priorities (multilevel feedback queuing)
  - If a thread is preempted by a timeout, it is penalized with lowered priority (bad thread)
  - If a thread suspends early, it is rewarded with raised priority (good thread)
  - High priority threads always preempt low priority threads
- Maybe it could be applied to the new GIL?

Remove the GIL?

- This entire talk has been about the problem of implementing <u>one</u> tiny little itty bitty lock
- Fixing Python to remove the GIL entirely is an exponentially more difficult project
- If there is one thing to take away, there are practical reasons why the GIL remains

Final Thoughts

- Don't use this talk to justify not using threads
- Threads are a very useful programming tool for many kinds of concurrency problems
- Threads can also offer excellent performance even with the GIL (you need to study it)
- However, you should know about the tricky corner cases

Final Thoughts

- Improving the GIL is something that all Python programmers should care about
- Multicore is not going away
- You might not use threads yourself, but they are used for a variety of low-level purposes in frameworks and libraries you might be using
- More predictable thread behavior is good

Thread Terminated

- That's it!
- Thanks for listening!
- Questions