# 15-410

# The Thread
# Jan. 24, 2011

**Dave Eckhardt**

***"Real concurrency – in which one program actually continues to function while you call up and use another – is more amazing but of small use to the average person. How many programs do you have that take more than a few seconds to perform any task?" – NYT, 4/25/1989***

# Synchronization

## Project 1

- By end of today...
  - Console (output) should be “doing something”, “not far”
  - Should have some progress for kbd, timer
    - » Should really have at least “solid design”
    - » Better to have handled one interrupt once

## Helpful hint?

- If you are having trouble with arrow keys when using X forwarding, try the numeric-keypad arrows

## Write good code

- Console driver will be used *(and extended)* in P3

# Readings

## Textbook chapters

- Already: Chapters 1 through 3
- Today: Chapter 4 (roughly)
- Soon: Chapters 6 & 7
  - Transactions (6.9) will be deferred
- Remember: reading schedule is on the “schedule” page

# Book Report Goals

**Some of you are going to grad. school**

**Some of you are wondering about grad. school**

**Some of you are *in* grad. school**

- **You should be able to read a Ph.D. dissertation**

**More generally**

- **Looking at something *in depth* is different**
- **Not like a textbook**

# Book Report Goals

**There's more than one way to do it**

- But you don't have time to try all the ways in 410
- Reading about other ways is good, maybe fun

**Habituation**

- Long-term career development requires study

**Writing skills (a little!)**

- “Summarizing” a book in a page is tough

# Book Report

**Read the "handout"**

**Browse the already-approved list**

**Pick something (soon)**

- "Don't make me stop the car..."

**Read a bit before you sleep at night**

- or: before you sleep in the morning
- and/or: Thanksgiving break / Spring break

**Assignment recommended by previous OS students!**

- They recommend starting early, too

# Road Map

**Thread lecture**

**Synchronization lectures**

- Probably *three*

**Yield lecture**

**This is important**

- When you leave here, you will use threads
- Understanding threads will help you understand the kernel

**Please make sure you *understand* threads**

- We'll try to help by assigning you P2

# Outline

**Thread = schedulable registers**

- (that's *all* there is)

**Why threads?**

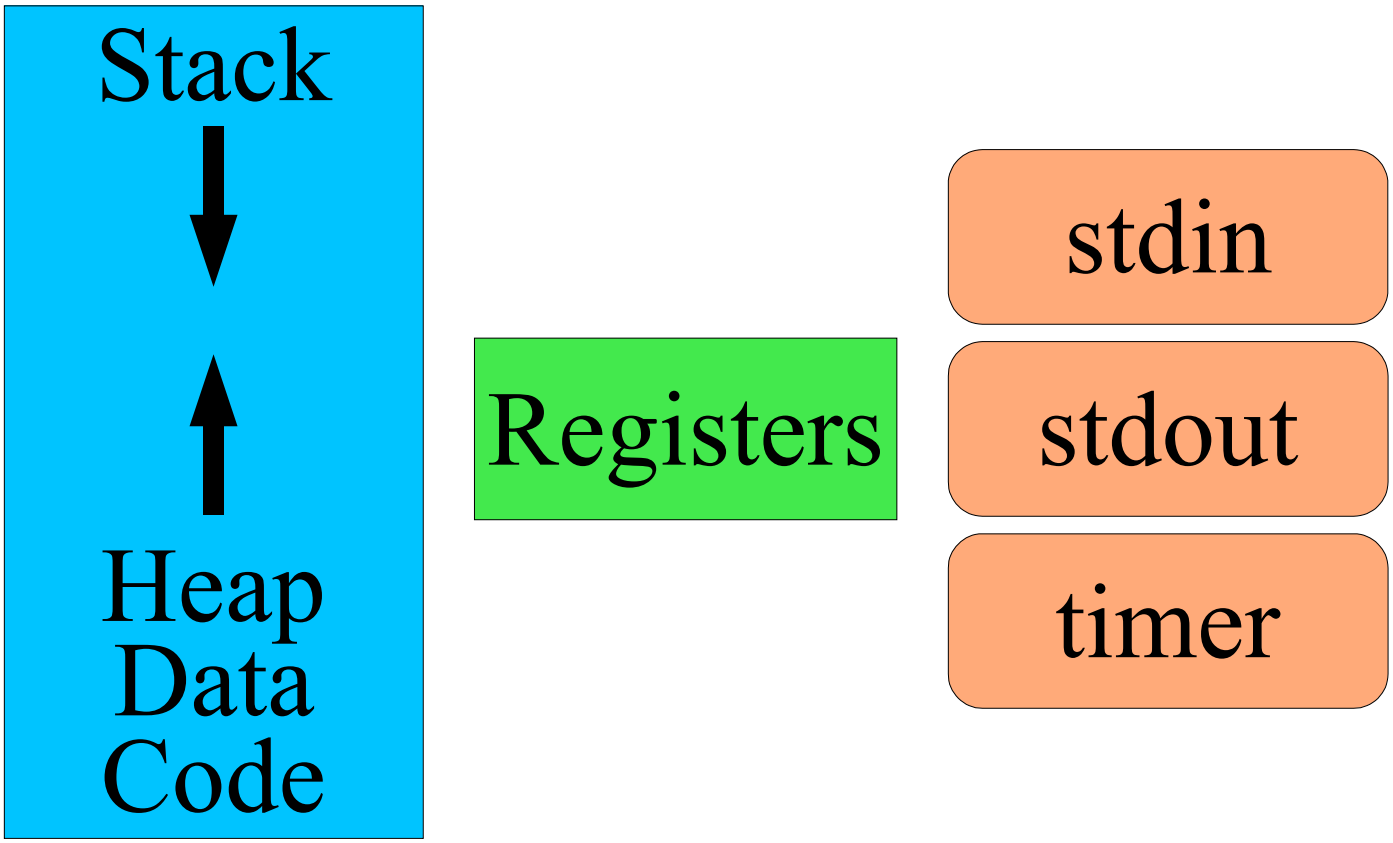
**Thread flavors (ratios)**

**(Against) cancellation**

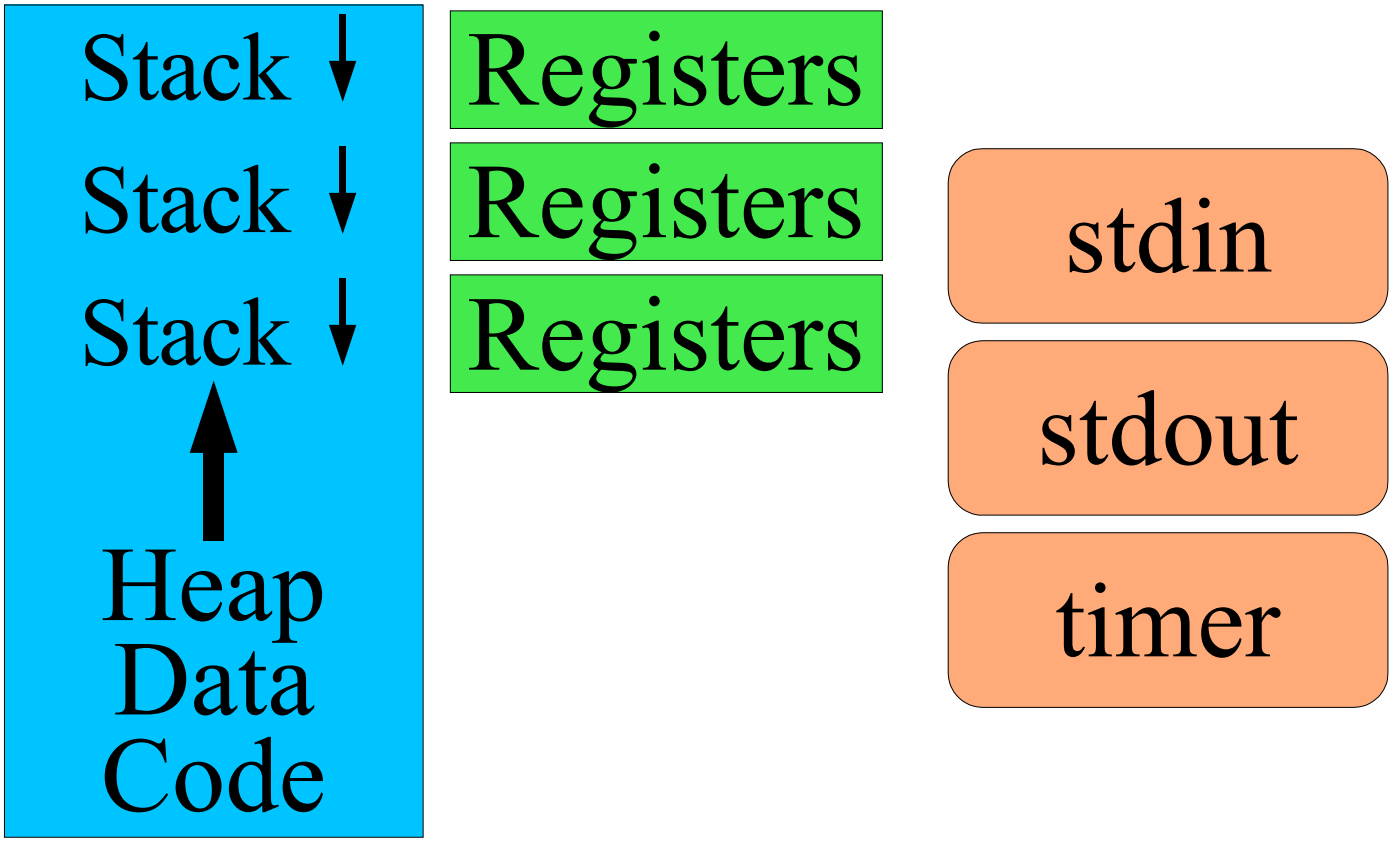
**Race conditions**

- 1 simple, 1 ouch
- *Make sure you really understand this*

# Single-threaded Process



# Multi-threaded Process



# What does that *mean*?

**Three stacks**

- Three sets of “local variables”

**Three register sets**

- Three stack pointers
- Three %eax's (etc.)

**Three *schedulable RAM mutators***

- (heartfelt but partial apologies to the ML crowd)

***Three potential bad interactions***

- A/B, A/C, B/C ... this pattern gets worse fast...

# Why threads?

**Shared access to data structures**

**Responsiveness**

**Speedup on multiprocessors**

# Shared access to data structures

## Database server for multiple bank branches

- Verify multiple rules are followed
  - Account balance
  - Daily withdrawal limit
- Multi-account operations (transfer)
- Many accesses, each modifies tiny fraction of database

## Server for a multi-player game

- Many players
- Access (& update) shared world state
  - Scan multiple objects
  - Update one or two objects

# Shared access to data structures

## Process per player?

- *Processes* share objects only via system calls
- Hard to make game objects = operating system objects

## Process per game object?

- "Scan multiple objects, update one"
- Lots of message passing between processes
- Lots of memory wasted for lots of processes
- *Slow*

# Shared access to data structures

***Thread*** **per player**

- Game objects inside single memory address space
- Each thread can access & update game objects
- Shared access to OS objects (files)

**Thread-switch is cheap**

- Store N registers
- Load N registers

# Responsiveness

**"Cancel" button vs. decompressing large JPEG**

- Handle mouse click *during* 10-second process
  - Map (x,y) to "cancel button" area
  - Change color / animate shadow / squeak / ...
  - Verify that button-release happens in button area of screen
- ...without JPEG decompressor understanding clicks
- Actually *stopping* the decompressor is a separate issue
  - Threads allow the user to register intent while it's running

# Multiprocessor speedup

**More CPUs can't help a single-threaded process!**

**PhotoShop color dither operation**

- Divide image into regions
- One dither thread per CPU
- Can (sometimes) get linear speedup

# Kinds of threads

**User-space (N:1)**

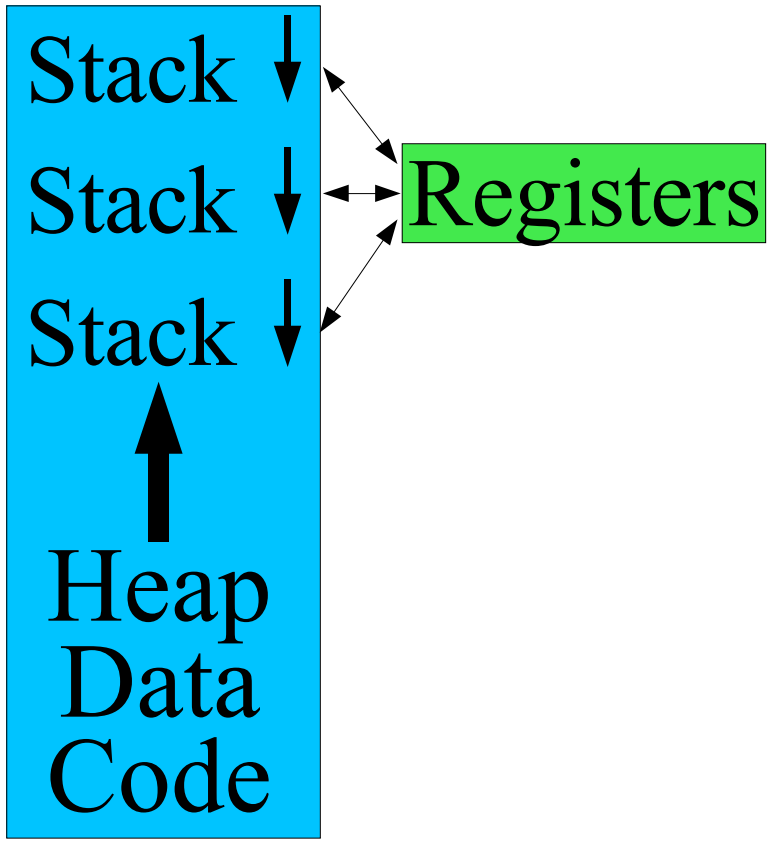
**Kernel threads (1:1)**

**Many-to-many (M :N)**

# User-space threads (N:1)

**Internal threading**

- Thread library adds threads to a process
- Thread switch "just swaps registers"
  - Small piece of asm code
  - Maybe called yield()



# User-space threads (N:1)

+ No change to operating system

- Any system call probably blocks all “threads”
  - “The process” makes a system call
  - Kernel blocks “the process”
  - (special non-blocking system calls can help)

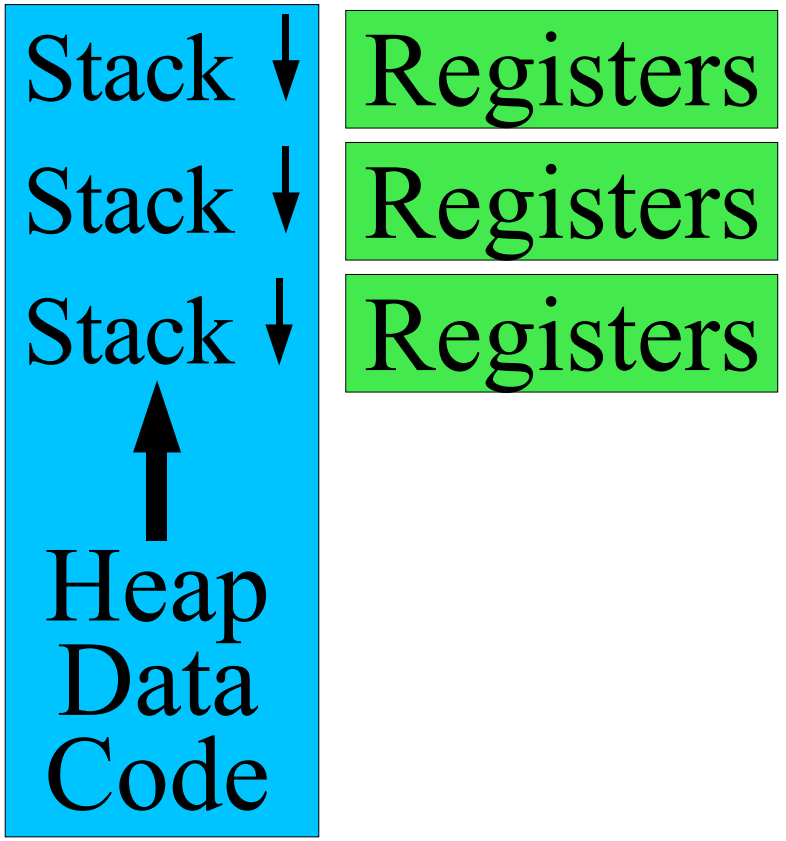
- “Cooperative scheduling” awkward/insufficient
  - Must manually insert many calls to yield()

- Cannot go faster on multiprocessor machines

# Pure kernel threads (1:1)

**OS-supported threading**

- OS knows thread/process ownership
- Memory regions shared & reference-counted



# Pure kernel threads (1:1)

**"Every thread is sacred"**

- Kernel-managed register set
- Kernel stack for when the thread is running kernel code
- "Real" (timer-triggered) scheduling

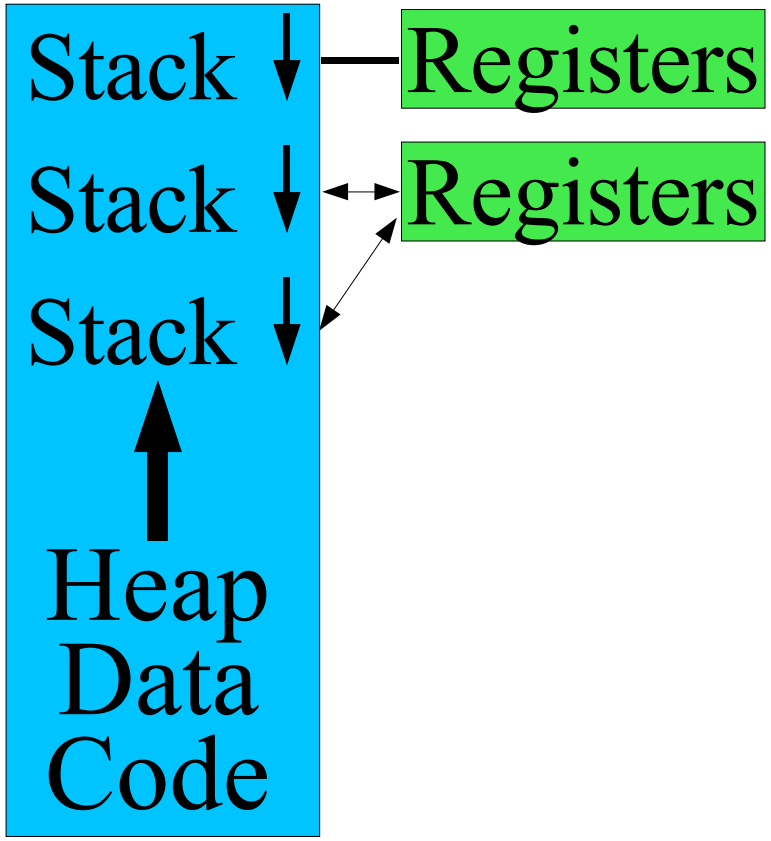
**Features**

+ Program runs faster on a multiprocessor
+ CPU-hog threads don't get all the CPU time
- User-space libraries must be rewritten to be "thread safe"
- Requires more kernel memory
  - 1 PCB ⇒ 1 TCB + N tCB's,
  - 1 k-stack ⇒ N k-stacks

# Many-to-many (M:N)

**Middle ground**

- OS provides kernel threads
- M user threads *share* N kernel threads



# Many-to-many (M:N)

## Sharing patterns

- Dedicated
  - User thread 12 owns kernel thread 1
- Shared
  - 1 kernel thread per hardware CPU
  - Each kernel thread executes next runnable user thread
- Many variations, see text

## Features

- Great when all the schedulers work together as you expected!

# (Against) Thread Cancellation

## Thread cancellation

- We don't want the result of that computation
  - ("Cancel button")
- Two kinds – "asynchronous", "deferred"

## Asynchronous (immediate) cancellation

- Stop execution *now*
  - Run 0 more instructions (at least, in user space)
  - Free stack, registers
  - Poof!
- Hard to garbage-collect resources (open files, ...)
- Difficult to maintain data-structure consistency!

# (Against) Thread Cancellation

## Deferred ("pretty please") cancellation

- Write down “Dear Thread #314, Please go away.”
- Threads must check for cancellation
- Or define safe cancellation points
  - “Any time I call close() it's ok to zap me”

## The only safe way

- Unless your threads are running very unusual code!

# Race conditions

**What you think**

```
ticket = next_ticket++; /* 0 ⇒ 1 */
```

**What really happens (in general)**

```
ticket = temp = next_ticket;      /* 0 */
++temp;                 /* 1, but not visible */
next_ticket = temp;     /* 1 is visible */
```

# Murphy' s Law (of threading)

**The world may *arbitrarily interleave* execution**

- **Multiprocessor**
  - **N threads executing instructions *at the same time***
  - **Of course effects are interleaved!**
- **Uniprocessor**
  - **Only one thread running at a time...**
  - **But N threads runnable, timer counting down toward zero...**

**The world will choose the *most painful* interleaving**

- **“Once chance in a million” happens every minute**

# Race Condition – Your Hope

| *T0* | | *T1* | |
|---|---|---|---|
| `tkt = tmp = n_tkt;` | 0 | | |
| `++tmp;` | 1 | | |
| `n_tkt = tmp;` | 1 | | |
| | | `tkt = tmp = n_tkt;` | 1 |
| | | `++tmp;` | 2 |
| | | `n_tkt = tmp;` | 2 |

**T0 has ticket 0, T1 has ticket 1. next_tkt has value 2. Your boss is happy.**

# Race Condition – Your Bad Luck

| *T0* | | *T1* | |
|---|---|---|---|
| `tkt = tmp = n_tkt;` | 0 | | |
| | | `tkt = tmp = n_tkt;` | 0 |
| `++tmp;` | 1 | | |
| | | `++tmp;` | 1 |
| `n_tkt = tmp;` | 1 | | |
| | | `n_tkt = tmp;` | 1 |

**T0 has ticket 0, T1 has ticket 0. next_tkt has value 1. Your boss is not entirely happy.**

# What happened?

**Each thread did "something reasonable"**

- ...assuming no other thread were touching those objects
- ...that is, assuming *"mutual exclusion"*

**The world is cruel**

- Any possible scheduling mix *will* happen sometime
- The one you fear will happen...
- The one you didn't think of will happen...

# The #! shell-script hack

**What's a "shell script"?**

- A file with a bunch of (shell-specific) shell commands

```
#!/bin/sh
echo "My hovercraft is full of eels."
sleep 10
exit 0
```

- Or: a security race-condition just waiting to happen...

# The #! shell-script hack

**What's "#!"?**

- A venerable hack

**You say**

- execl("/foo/script", "script", "arg1", 0);

**/foo/script “executable file” begins...**

- #!/bin/sh

**The kernel rewrites your system call...**

- execl("/bin/sh" "/foo/script" "arg1" , 0);

**The shell does**

- open("/foo/script", O_RDONLY, 0);

# The setuid invention

## U.S. Patent #4,135,240

- Dennis M. Ritchie
- January 16, 1979

## The concept

- A program with *stored privileges*
- When executed, runs with *two* identities
  - invoker's identity
  - program owner's identity
- Can switch identities at will
  - Open some files as invoker
  - Open other files as program-owner

# Setuid example - printing a file

## Goals

- Every user can queue files
- Users cannot delete other users' files

## Solution

- Queue directory owned by user `printer`
- Setuid `queue-file` program
  - Create queue file as user `printer`
  - Copy joe's data as user `joe`
- Also, setuid `remove-file` program
  - Allows removal only of files you queued
- User `printer` mediates user `joe`'s queue access

# Race condition example

| *Process 0* | *Process 1* |
|---|---|
| `ln -s /bin/lpr /tmp/lpr` | |
| | `run /tmp/lpr` |
| | `[setuid to user "printer"]` |
| | `start "/bin/sh /tmp/lpr..."` |
| `rm /tmp/lpr` | |
| `ln -s /my/exploit /tmp/lpr` | |
| | `script = open("/tmp/lpr");` |
| | `execute /my/exploit` |

# What happened?

## Intention

- Assign privileges to program contents

## What happened?

- First, name was mapped to privileges
  - (name ⇒ file, file ⇒ privileges)
- Next, program name was re-bound to a different file
- Then, name was mapped to contents
  - (name ⇒ different file, different file ⇒ different contents)

## How would you fix this?

# How to solve race conditions?

**Carefully analyze operation sequences**

**Find subsequences which must be *uninterrupted***

- **"Critical section"**

**Use a *synchronization mechanism***

- **Next time!**

# Summary

**Thread: What, why**

**Thread flavors (ratios)**

**Race conditions**

- ***Make sure you really understand this***

# Further Reading

## Setuid Demystified

- Hao Chen, David Wagner, Drew Dean
- http://www.cs.berkeley.edu/~daw/papers/setuid-usenix02.pdf
- “Abandon hope all ye who enter here”

## The “cancel button problem”

- Gregory S. Hartman
- “Attentiveness: Reactivity at Scale”
- CMU-ISR-10-111.pdf