Principles of Software Construction: Objects, Design, and Concurrency

The Perils of Concurrency

Can't live with it.
Can't live without it.

Fall 2014

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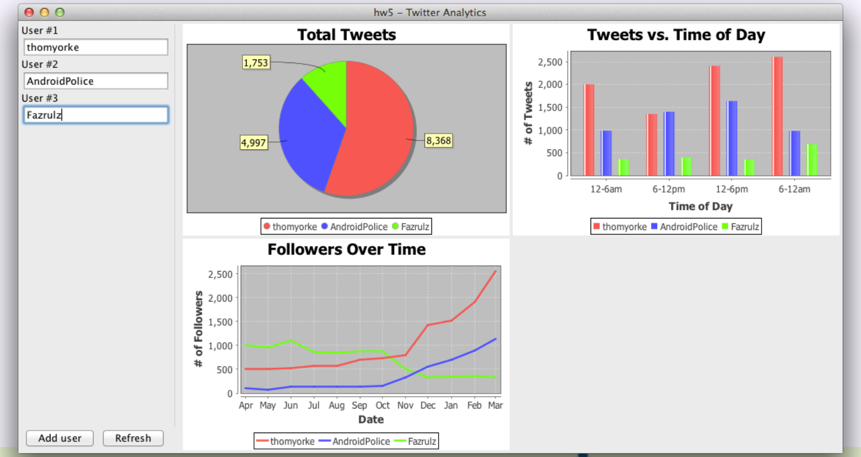
Administrivia

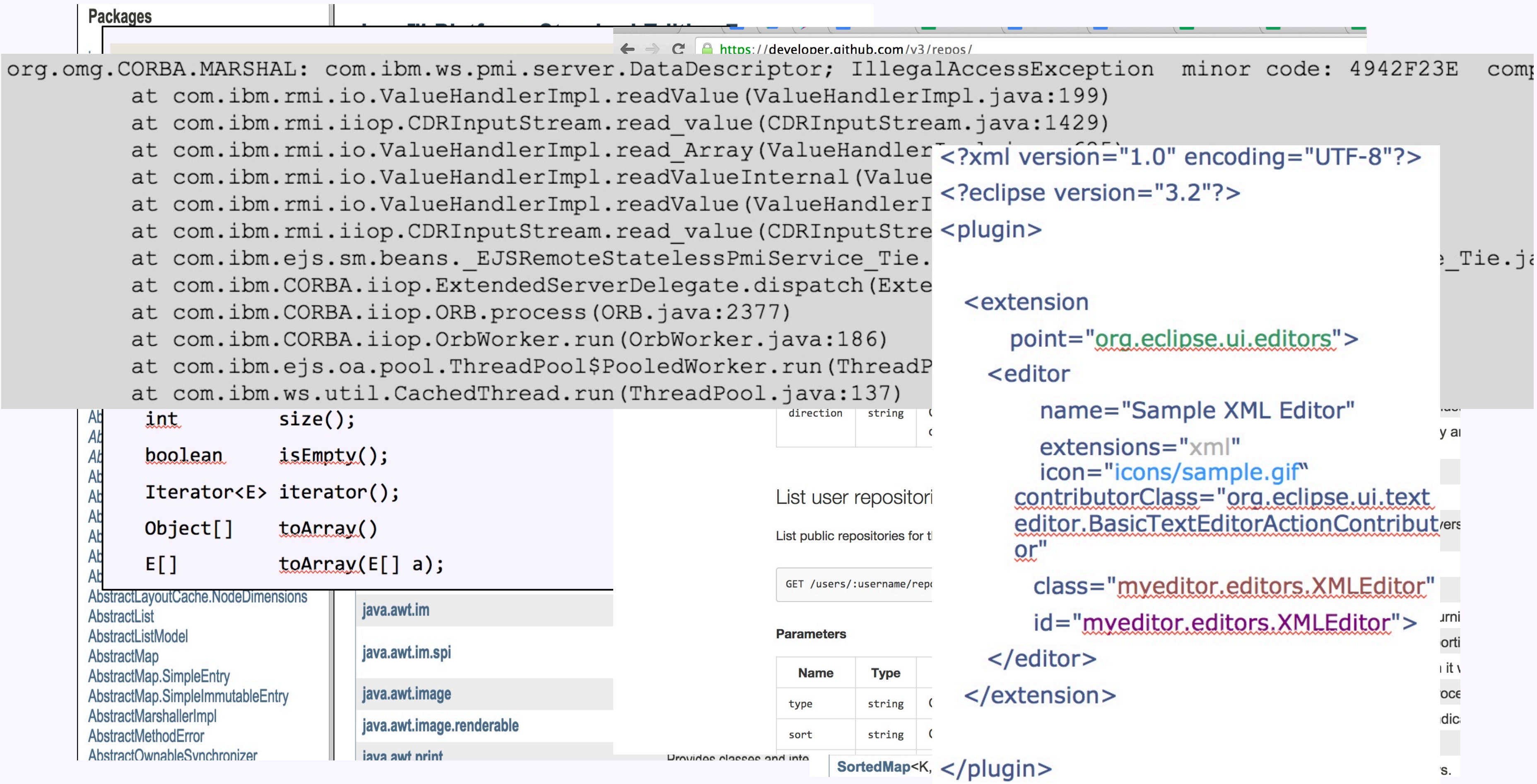
- Homework 4c due tonight
  - Remember to add an `ant run` target
- 2nd midterm exam Thursday
  - Review session tonight, 5-7 p.m. in PH 100
- Homework 5 released by tomorrow
  - Must select partner(s) by Thursday (30 Oct)
  - 5a due next Wednesday morning (05 Nov)
  - 5b due the following Thursday (13 Nov)
  - 5c due the following Thursday (20 Nov)



Key concepts from last Thursday

API: Application Programming Interface

- An API defines the boundary between components/modules in a programmatic system



An API design process

- Define the scope of the API
  - Collect use-case stories, define requirements
  - Be skeptical
    - Distinguish true requirements from so-called solutions
    - "When in doubt, leave it out."
- Draft a specification, gather feedback, revise, and repeat
  - Keep it simple, short
- Code early, code often
  - Write *client code* before you implement the API

Key design principle: Information hiding

- "When in doubt, leave it out."

Minimize mutability

- Immutable objects are:
  - Inherently thread-safe
  - Freely shared without concern for side effects
  - Convenient building blocks for other objects
  - Can share internal implementation among instances
    - See `java.lang.String`
- Mutable objects require careful management of visibility and side effects
  - e.g. `Component.getSize()` returns a mutable `Dimension`
- Document mutability
  - Carefully describe state space

The four course themes

- Threads and concurrency
  - Concurrency is a crucial system abstraction
  - E.g., background computing while responding to users
  - Concurrency is necessary for performance
  - Multicore processors and distributed computing
  - Our focus: application-level concurrency
  - Cf. functional parallelism (150, 210) and systems concurrency (213)
- Object-oriented programming
  - For flexible designs and reusable code
  - A primary paradigm in industry – basis for modern frameworks
  - Focus on Java – used in industry, some upper-division courses
- Analysis and modeling
  - Practical specification techniques and verification tools
  - Address challenges of threading, correct library usage, etc.
- Design
  - Proposing and evaluating alternatives
  - Modularity, information hiding, and planning for change
  - Patterns: well-known solutions to design problems

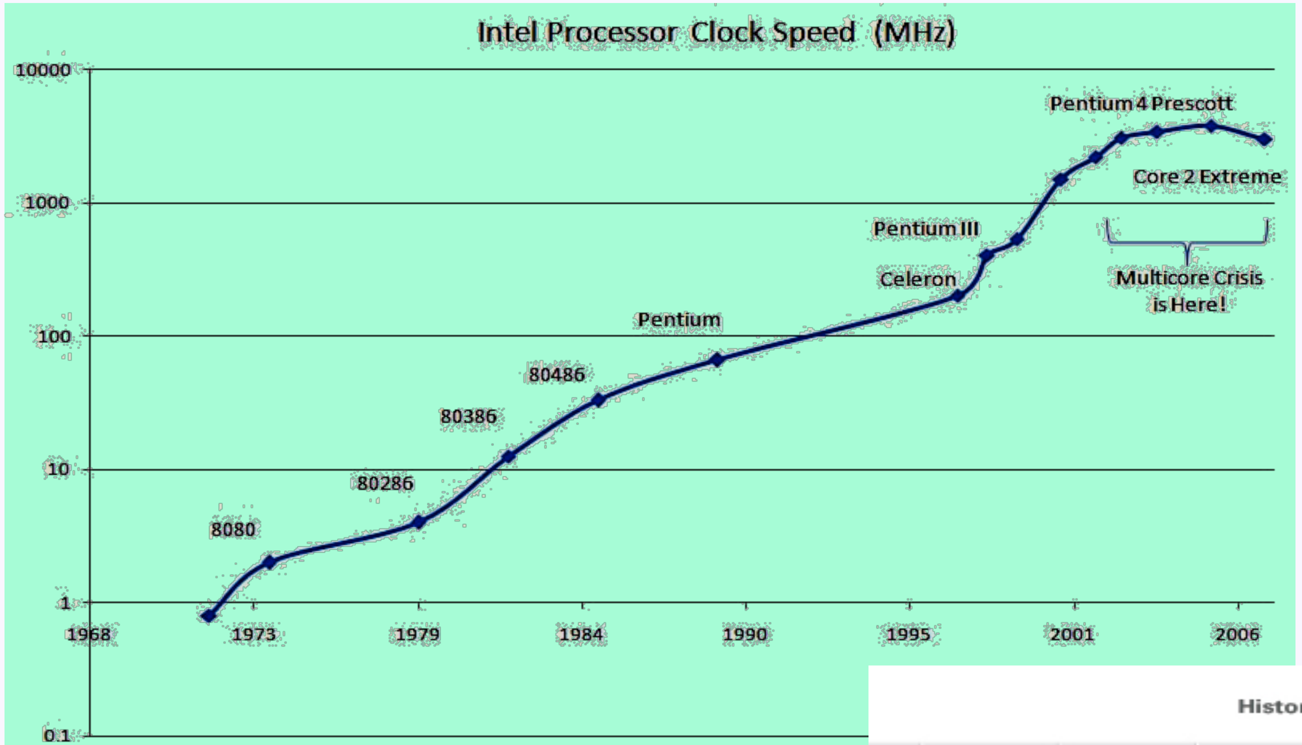
Today: Concurrency, part 1

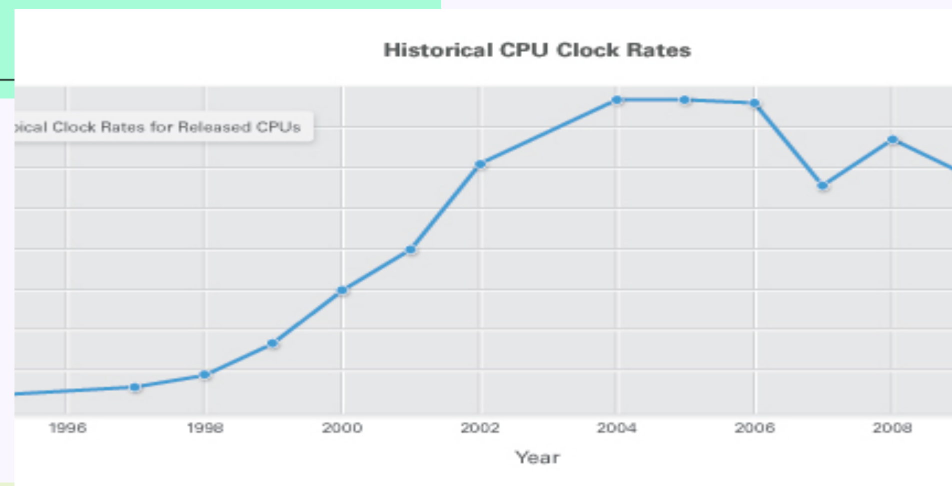
- The backstory
  - Motivation, goals, problems, …
- Basic concurrency in Java
  - Synchronization
- Coming soon (but not today):
  - Higher-level abstractions for concurrency
    - Data structures
    - Computational frameworks

Learning goals

- Understand concurrency as a source of complexity in software
- Know common abstractions for parallelism and concurrency, and the trade-offs among them
  - Explicit concurrency
    - Write thread-safe concurrent programs in Java
    - Recognize data race conditions
  - Know common thread-safe data structures, including high-level details of their implementation
  - Understand trade-offs between mutable and immutable data structures
  - Know common uses of concurrency in software design

Processor speeds over time



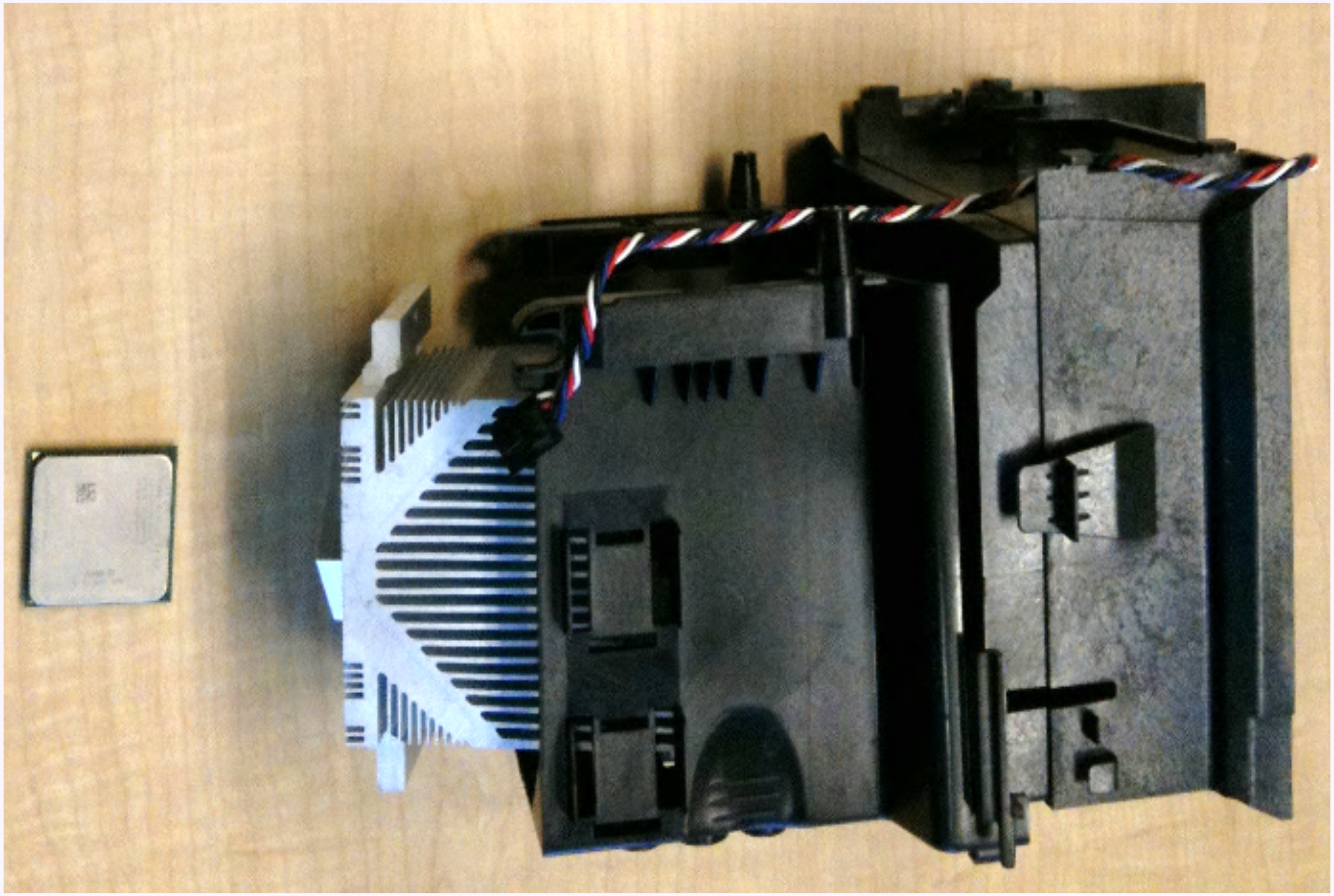


Power requirements of a CPU

- Approx.: **C**apacitance * **V**oltage^2 * **F**requency
- To increase performance:
  - More transistors, thinner wires: more **C**
    - More power leakage: increase **V**
  - Increase clock frequency **F**
    - Change electrical state faster: increase **V**
- Problem: Power requirements are super-linear to performance
  - Heat output is proportional to power input

One option: fix the symptom

- Dissipate the heat



One option: fix the symptom

- Better: Dissipate the heat with liquid nitrogen
  - Overclocking by Tom's Hardware's 5 GHz project

http://www.tomshardware.com/reviews/5-ghz-project,731-8.html

Another option: fix the underlying problem

- Reduce heat by limiting power input
  - Adding processors increases power requirements linearly with performance
    - Reduce power requirement by reducing the frequency and voltage
    - Problem: requires concurrent processing

Aside: Three sources of disruptive innovation

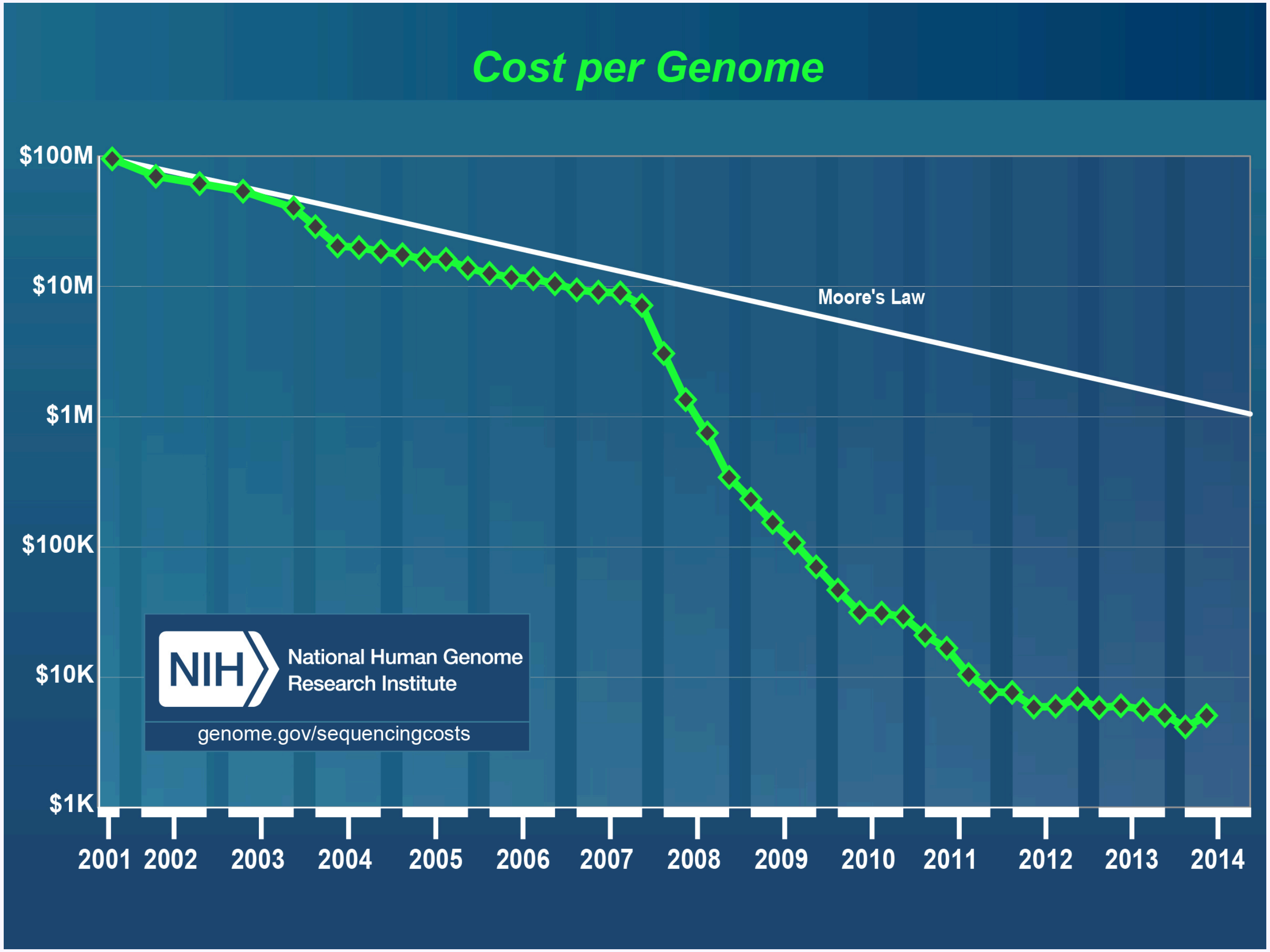
- Growth crosses some threshold
  - e.g., Concurrency: ability to add transistors exceeded ability to dissipate heat
- Colliding growth curves
  - Rapid design change forced by jump from one curve onto another
- Network effects
  - Amplification of small triggers leads to rapid change

Aside: The threshold for distributed computing

- Too big for a single computer?
  - Forces use of distributed architecture
    - Shifts responsibility for reliability from hardware to software
      - Allows you to buy larger cluster of cheap flaky machines instead of expensive slightly-less-flaky machines
        - Revolutionizes data center design

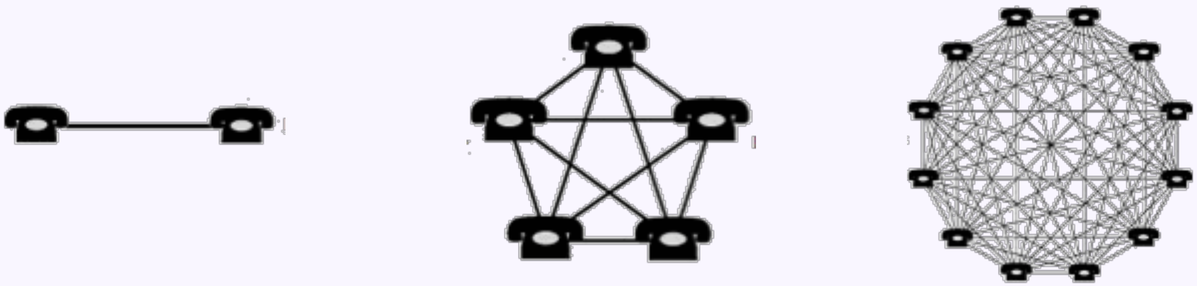
Aside: Colliding growth curves

- From http://www.genome.gov/sequencingcosts/



Aside: Network effects

- Metcalfe's rule: network value grows quadratically in the number of nodes
  - a.k.a. Why my mom has a Facebook account
  - `n(n-1)/2` potential connections for `n` nodes



  - Creates a strong imperative to merge networks
    - Communication standards, USB, media formats, ...

Concurrency

- Simply: doing more than one thing at a time
  - In software: more than one point of control
    - Threads, processes
- Resources simultaneously accessed by more than one thread or process

Concurrency then and now

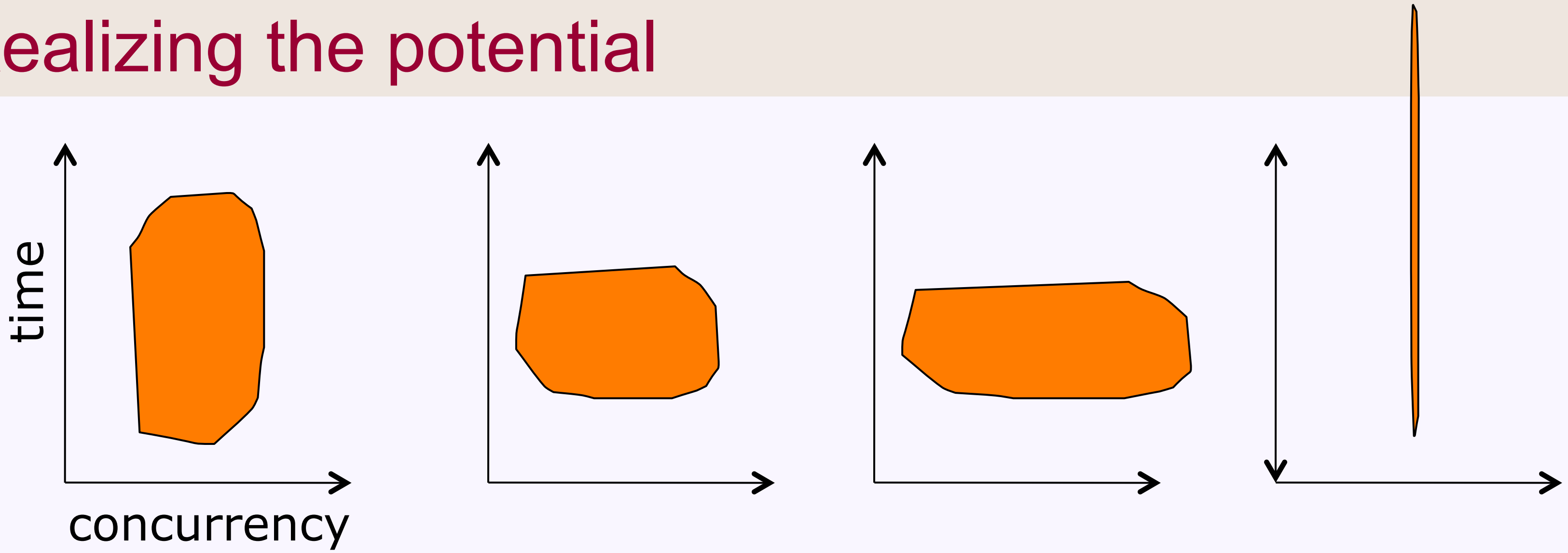
- In the past multi-threading was just a convenient abstraction
  - GUI design: event threads
  - Server design: isolate each client's work
  - Workflow design: producers and consumers
- Now: must use concurrency for scalability and performance

Image Name	Threads
IPSSVC.EXE	86
svchost.exe	82
System	80
afsd_service.exe	51
Rtvscan.exe	47
winlogon.exe	39
explorer.exe	20
ccEvtMgr.exe	19
svchost.exe	18
lsass.exe	18
tabtip.exe	17
svchost.exe	17
firefox.exe	16
services.exe	16
thunderbird.exe	15
csrss.exe	13
tcserver.exe	10
KeyboardSurroga...	10
spoolsv.exe	10
tvt_reg_monitor_...	10
svchost.exe	10
POWERPNT.EXE	9
taskmgr.exe	8
VPTray.exe	8
S24EvMon.exe	8
EvtEng.exe	8
emacs.exe	7
tvtsched.exe	7
ibmpmsvc.exe	7
AcroRd32.exe	7
vpngui.exe	6
cvpnd.exe	6
AluSchedulerSvc....	6
ccSetMgr.exe	6
svchost.exe	6
wisptis.exe	5
alg.exe	5
TPHKMGR.exe	5
ASRSVC.exe	5

Problems of concurrency

- Realizing the potential
  - Keeping all threads busy doing useful work
- Delivering the right language abstractions
  - How do programmers think about concurrency?
  - Aside: parallelism vs. concurrency
- Non-determinism
  - Repeating the same input can yield different results

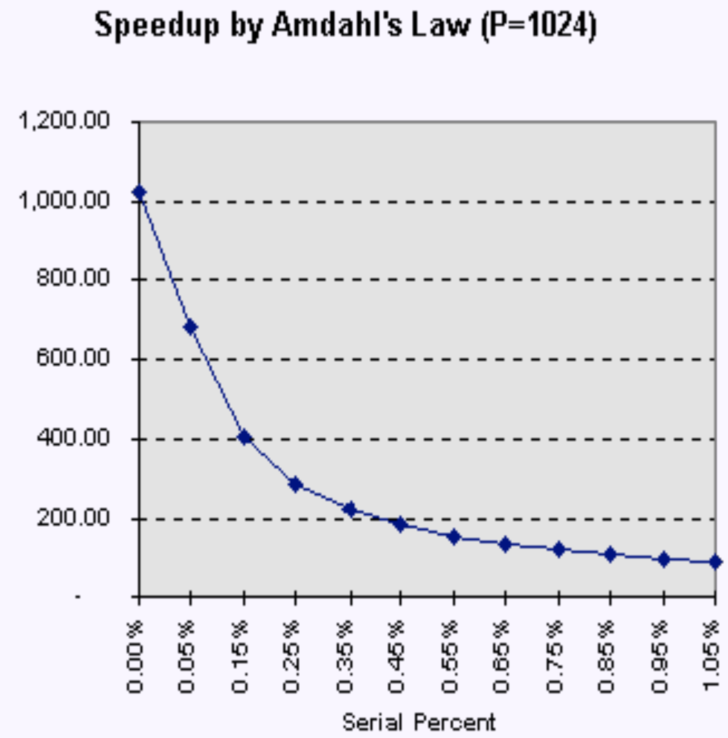
Realizing the potential



- Possible metrics of success
  - Breadth: extent of simultaneous activity
    - width of the shape
  - Depth (or span): length of longest computation
    - height of the shape
  - Work: total effort required
    - area of the shape
- Typical goals in parallel algorithm design?

Amdahl's law: How good can the depth get?

- Ideal parallelism with `N` processors:
  - Speedup = `N`
- In reality, some work is always inherently sequential
  - Let `F` be the portion of the total task time that is inherently sequential
  - Speedup = $\frac{1}{F + (1 - F)/N}$



  - Suppose F = 10%. What is the max speedup? (you choose `N`)

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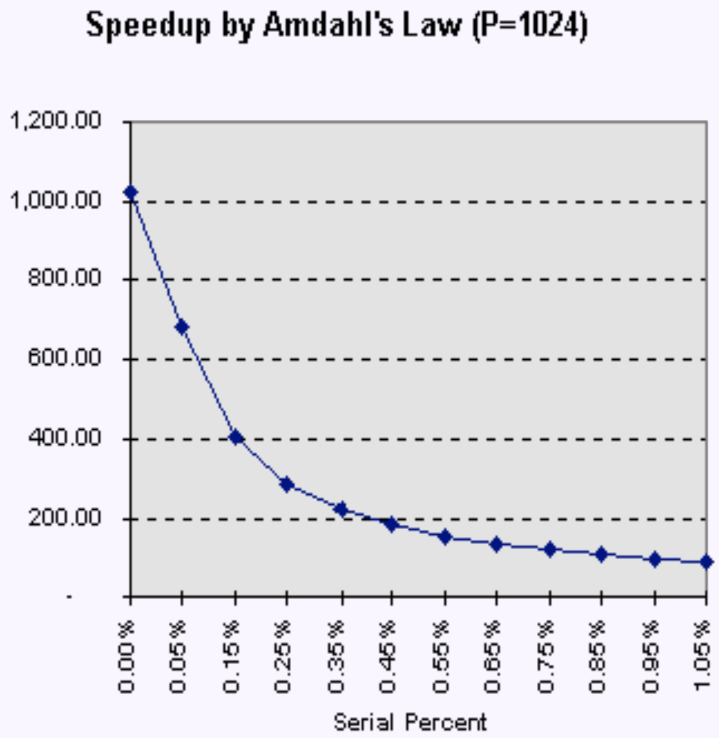
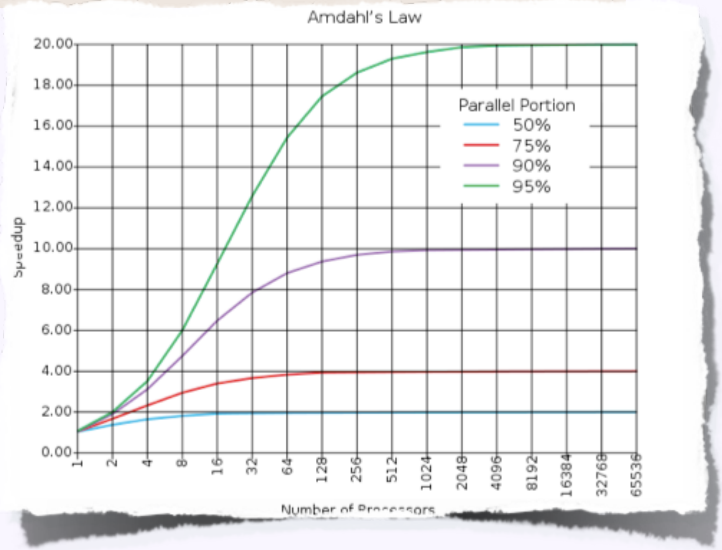


  - Suppose F = 10%. What is the max speedup? (you choose N)
    - As N approaches ∞, 1/(0.1 + 0.9/N) approaches 10.

Using Amdahl's law as a design guide

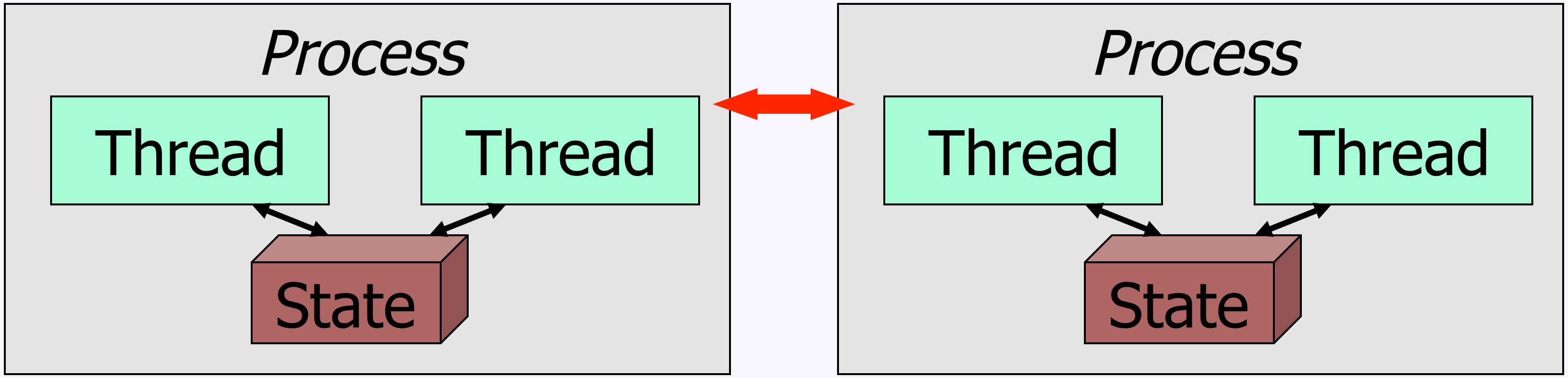


- For a given algorithm, suppose
  - `N` processors
  - Problem size `M`
  - Sequential portion `F`
- An obvious question:
  - What happens to speedup as `N` scales?
- A less obvious, important question:
  - What happens to `F` as problem size `M` scales?

"For the past 30 years, computer performance has been driven by Moore's Law; from now on, it will be driven by Amdahl's Law."
— Doron Rajwan, Intel Corp

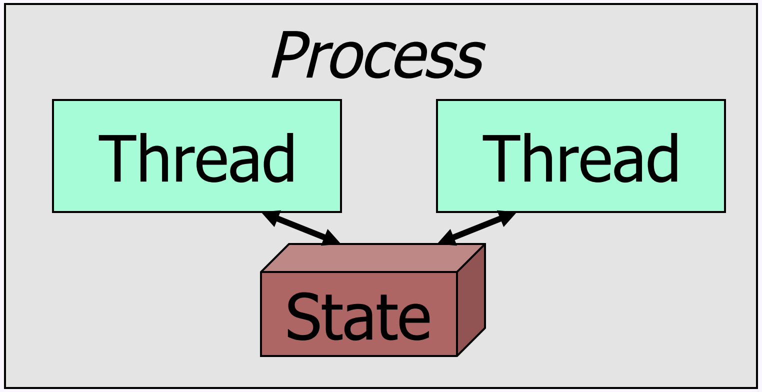
Abstractions of concurrency

- Processes
  - Execution environment is isolated
    - Processor, in-memory state, files, …
  - Inter-process communication typically slow, via message passing
    - Sockets, pipes, …
- Threads
  - Execution environment is shared
  - Inter-thread communication typically fast, via shared state

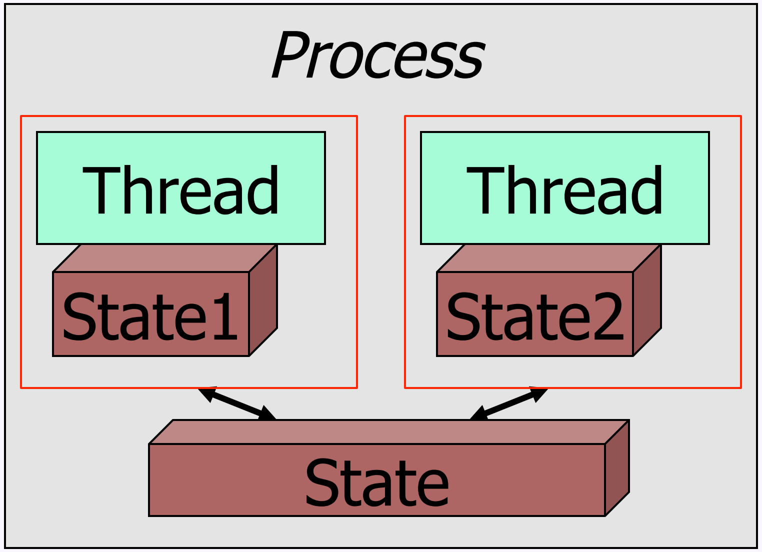


Aside: Abstractions of concurrency

- What you see:
  - State is all shared



- A (slightly) more accurate view of the hardware:
  - Separate state stored in registers and caches
  - Shared state stored in caches and memory



Basic concurrency in Java

- The `java.lang.Runnable` interface

```
void           run();
```

- The `java.lang.Thread` class

```
Thread(Runnable r);
void           start();
static void    sleep(long millis);
void           join();
boolean        isAlive();
static Thread currentThread();
```

- See IncrementTest.java

Atomicity

- An action is *atomic* if it is indivisible
  - Effectively, it happens all at once
    - No effects of the action are visible until it is complete
    - No other actions have an effect during the action
- In Java, integer increment is not atomic

`i++;` is actually

1. Load data from variable `i`
2. Increment data by `1`
3. Store data to variable `i`

One concurrency problem: race conditions

- A *race condition* is when multiple threads access shared data and unexpected results occur depending on the order of their actions

- E.g., from IncrementTest.java:
  - Suppose `classData` starts with the value 41:

Thread A:

```
classData++;
```

Thread B:

```
classData++;
```

One possible interleaving of actions:

1A. Load data(41) from `classData`

1B. Load data(41) from `classData`

2A. Increment data(41) by 1 -> 42

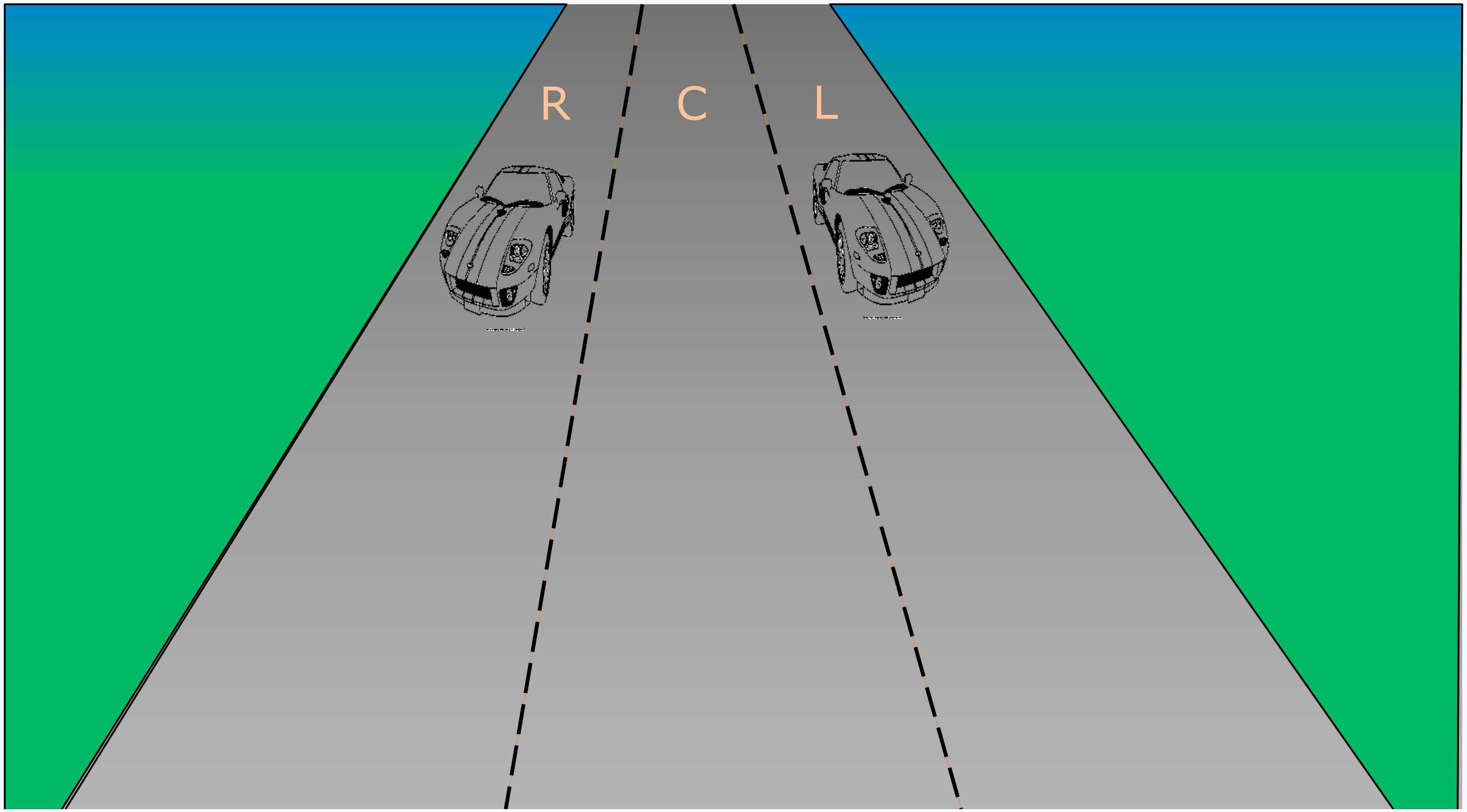
2B. Increment data(41) by 1 -> 42

3A. Store data(42) to `classData`

3B. Store data(42) to `classData`

Race conditions in real life

- E.g., check-then-act on the highway



Race conditions in real life

- E.g., check-then-act at the bank
  - The "debit-credit problem"

Alice, Bob, Bill,* and the *Bank

- **A. *Alice* to pay *Bob* $30**
  - **Bank actions**
    1. **Does Alice have $30 ?**
    2. **Give $30 to *Bob***
    3. **Take $30 from *Alice***
- **B. *Alice* to pay *Bill* $30**
  - **Bank actions**
    1. **Does Alice have $30 ?**
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- **If *Alice* starts with $40, can *Bob* and *Bill* both get $30?**

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A.1
A.2
B.1
B.2
A.3
B.3!

Race conditions in *your* real life

- E.g., check-then-act in simple code

```
public class StringConverter {
    private Object o;
    public void set(Object o) {
        this.o = o;
    }
    public String get() {
        if (o == null) return "null";
        return o.toString();
    }
}
```

  - See StringConverter.java, Getter.java, Setter.java

Some actions are atomic

Precondition:

```
int i = 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

Some actions are atomic

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i: **00000…00000111**

⋮

i: **00000…00101010**

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`i:` **00000…00000111**

⋮

`i:` **00000…00101010**

- In Java:
  - Reading an int variable is atomic
  - Writing an int variable is atomic
  - Thankfully, `ans:` **00000…00101111** is not possible

Bad news: some simple actions are not atomic

- Consider a single 64-bit `long` value

high bits	low bits

  - Concurrently:
    - Thread A writing high bits and low bits
    - Thread B reading high bits and low bits

Precondition:

```
long i = 10000000000;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

`ans:`	01001…00000000	(10000000000)
`ans:`	00000…00101010	(42)
`ans:`	01001…00101010	(10000000042 or …)

Thursday:

- Midterm exam…
- Next week:
  - Primitive concurrency control
  - …then higher abstractions