Principles of Software Construction: Objects, Design and Concurrency

The Perils of Concurrency (Can't live with it, can't live without it.)

15-214

toad

Spring 2013

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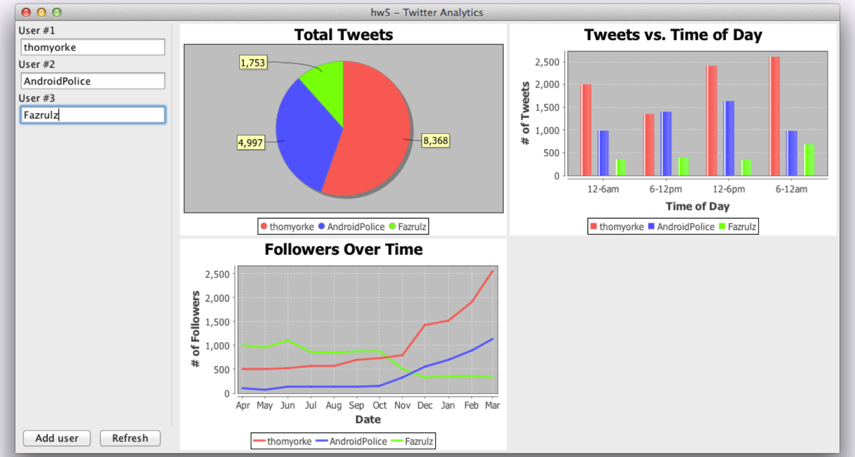
Administrivia

- Homework 4c due tonight
- Homework 5 coming soon
  - Must select partner(s) by Thursday (28 March)
  - 5a due next Wednesday (03 April)
  - 5b due the following Wednesday (10 April)
  - 5c due the following Tuesday (16 April)
- Final exam is Monday 13 May, 5:30 – 8:30 p.m.

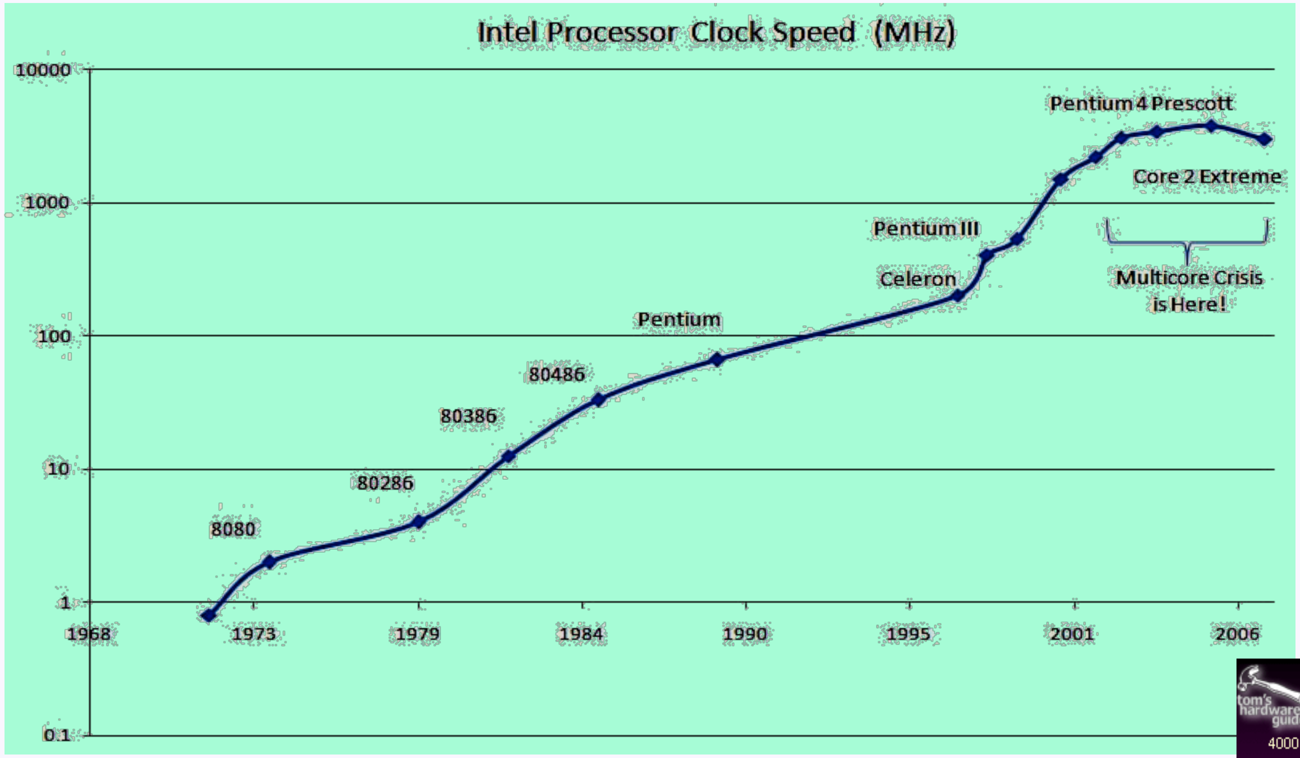


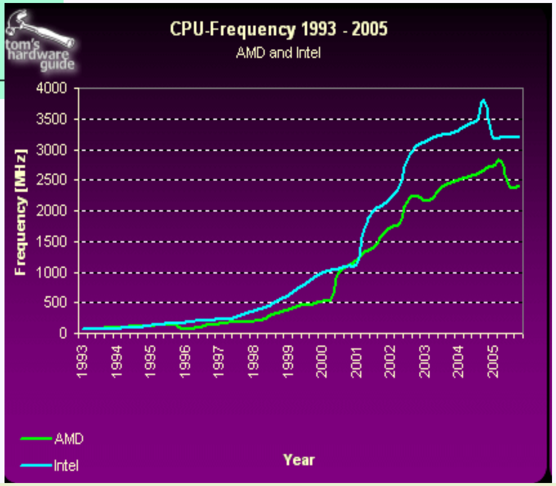
Key topics from last Thursday

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

Processor speeds over time



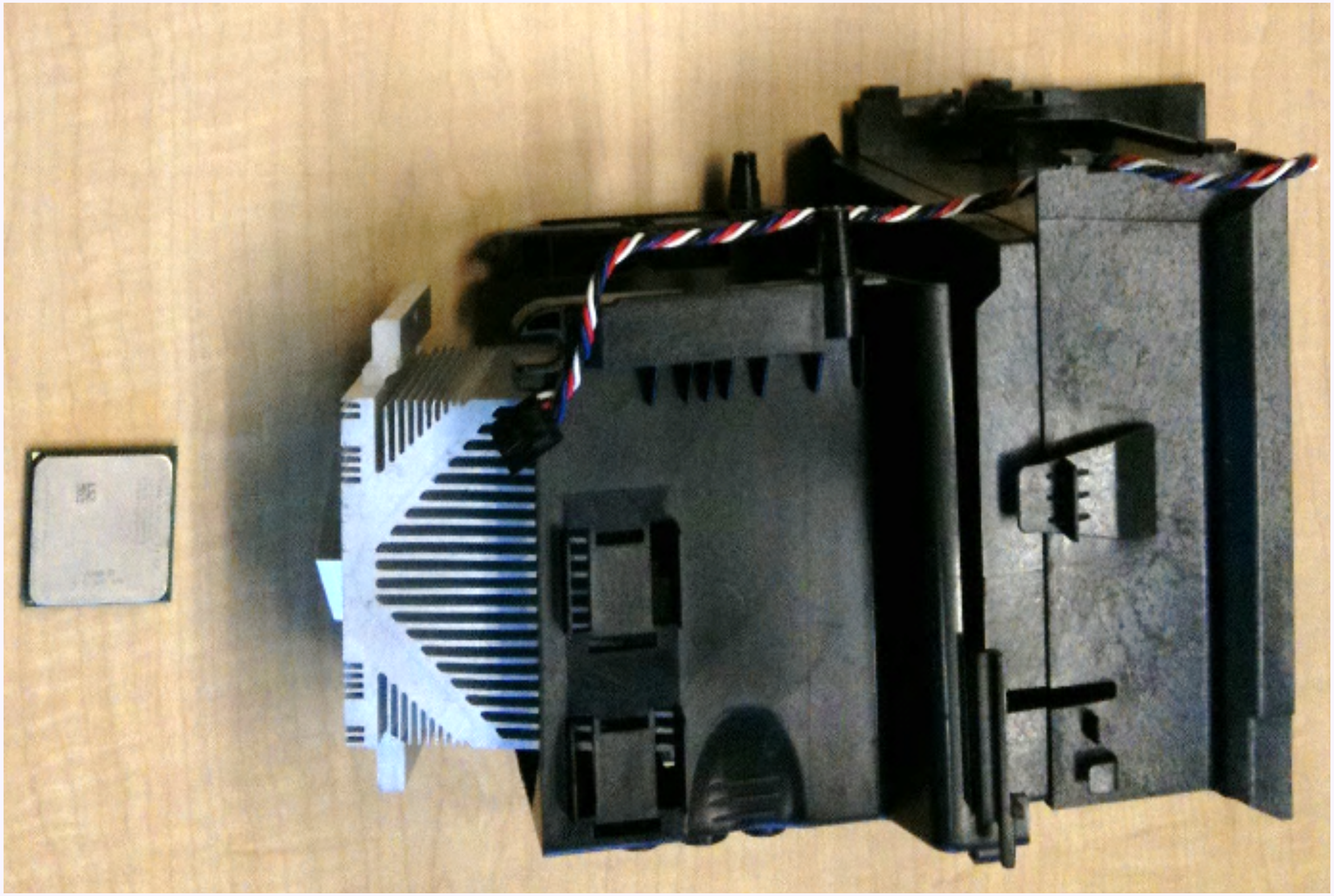


Power requirements of a CPU

- 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

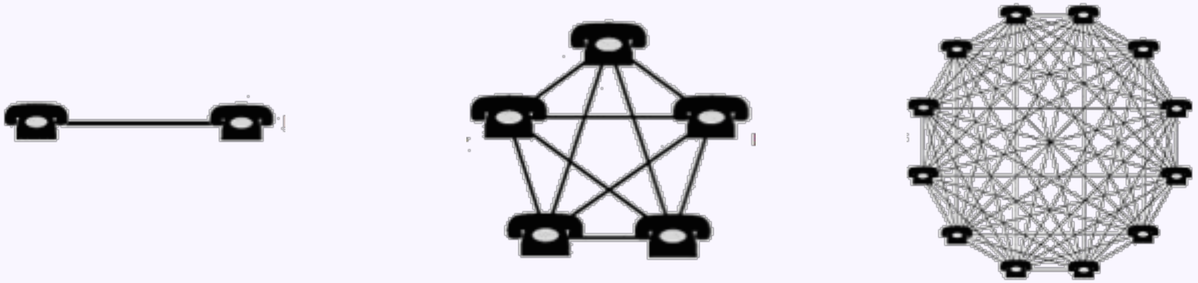
- Growth crosses some threshold
  - e.g., Concurrency: ability to add transistors exceeded ability to dissipate heat
- Colliding growth curves
  - Rapid design change forced by jump from one curve onto another
- Network effects
  - Amplification of small triggers leads to rapid change

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 cheap flaky machines instead of expensive somewhat-flaky machines
        - Revolutionizes data center design

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



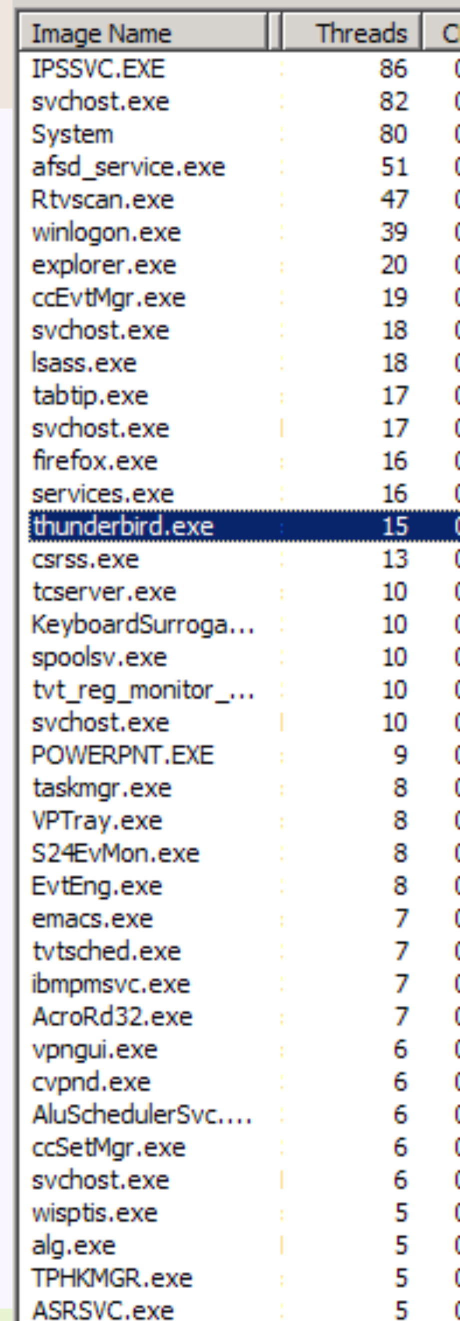
  - Creates a strong imperative to merge networks
    - Communication standards, USB, media formats, ...

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

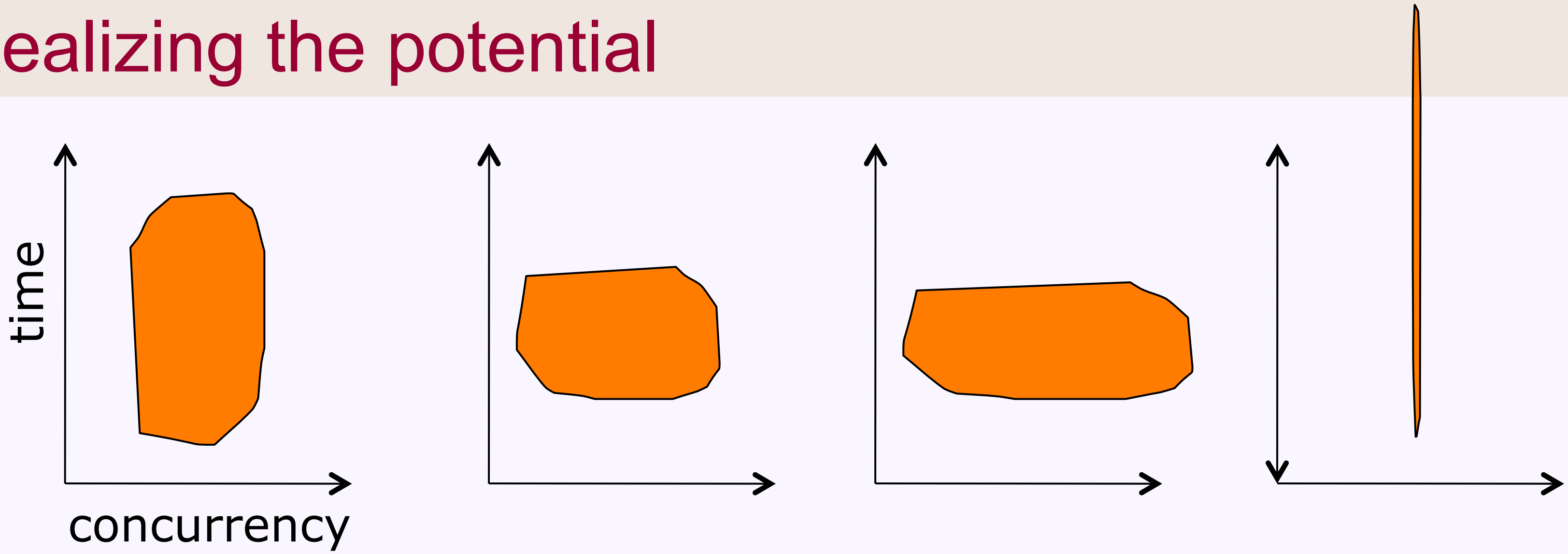
- In the past multi-threading was just a convenient abstraction
  - GUI design: event threads
  - Server design: isolate each client's work
  - Workflow design: producers and consumers
- Now: must use concurrency for scalability and performance



Problems of concurrency

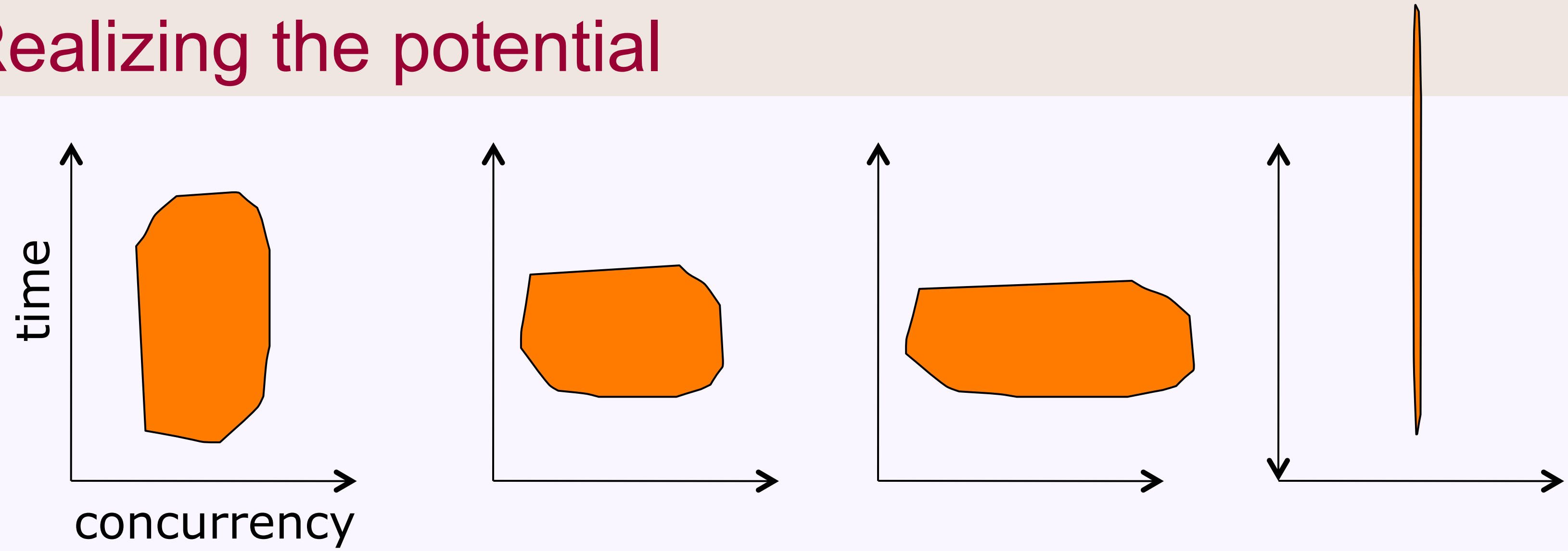
- Realizing the potential
  - Keeping all threads busy doing useful work
- Delivering the right language abstractions
  - How do programmers think about concurrency?
  - Aside: parallelism vs. concurrency
- Non-determinism
  - Repeating the same input can yield different results

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?

Realizing the potential



- Possible metrics of success
  - Breadth: extent of simultaneous activity
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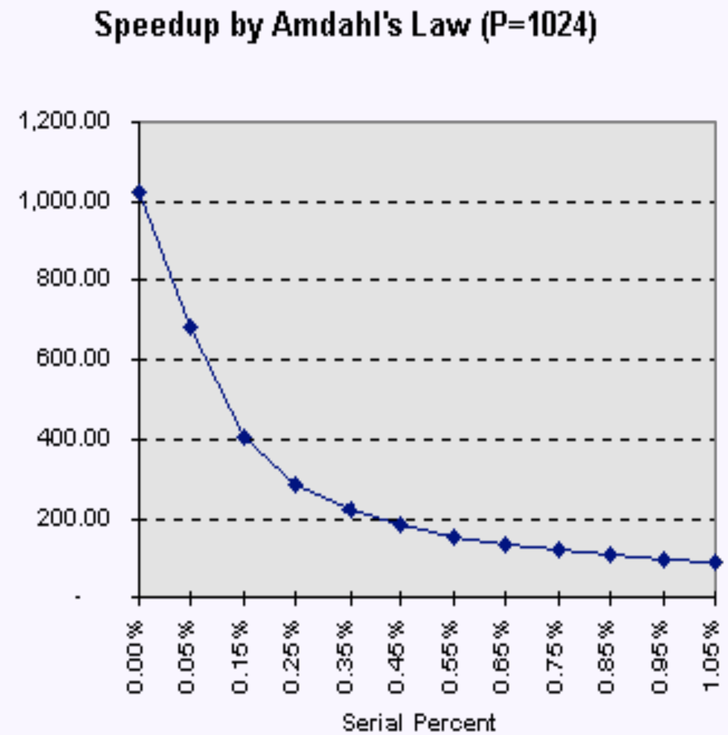
  - Depth (or span): length of longest computation
    - height of the shape
  - Work: total effort required
    - area of the shape
- Typical goals in parallel algorithm design?
  - First minimize depth (total time we wait), then minimize work

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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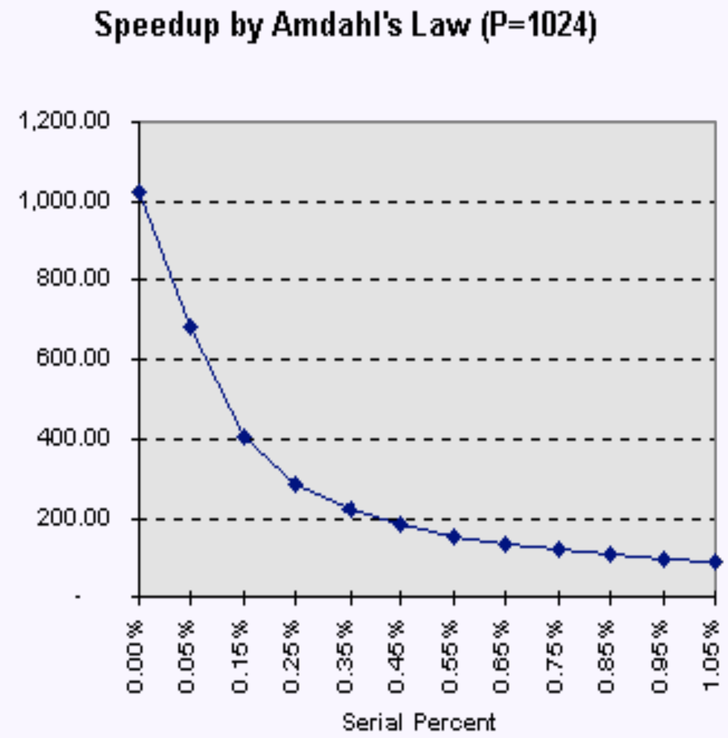

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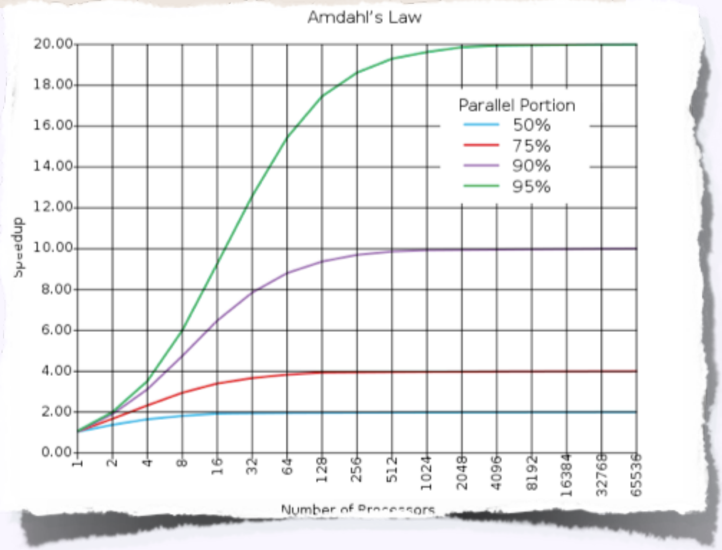
  - Let F be the portion of the total task time that is inherently sequential
  - Speedup = $\frac{1}{F + (1 - F)/N}$
  - Suppose F = 10%. What is the max speedup? (you choose N)
    - As N approaches ∞, 1/(0.1 + 0.9/N) approaches 10.

Using Amdahl's law as a design guide



- For a given algorithm, suppose
  - `N` processors
  - Problem size `M`
  - Sequential portion `F`

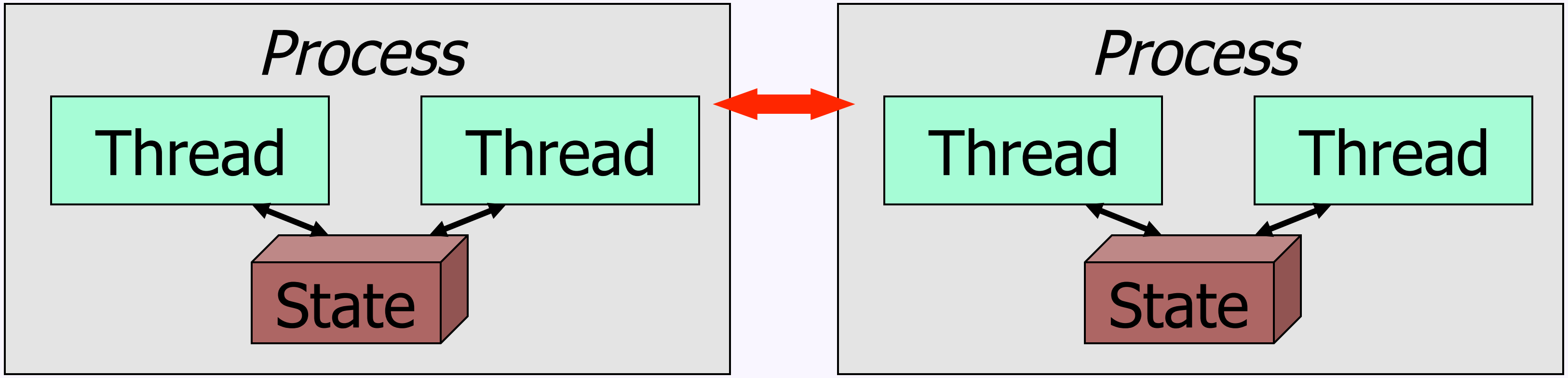
- An obvious question:
  - What happens to speedup as `N` scales?

- Another 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

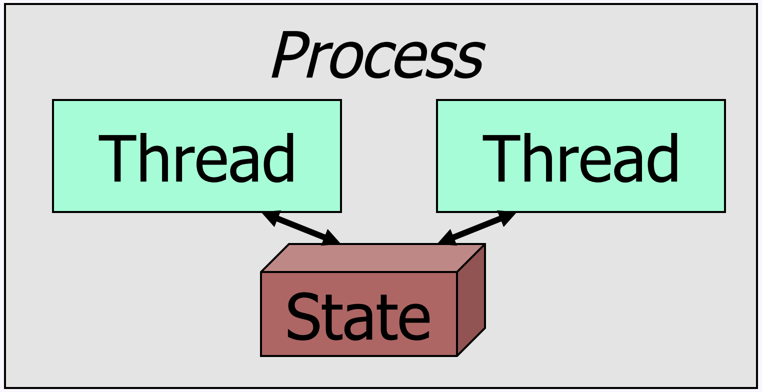
Abstractions of concurrency

- 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

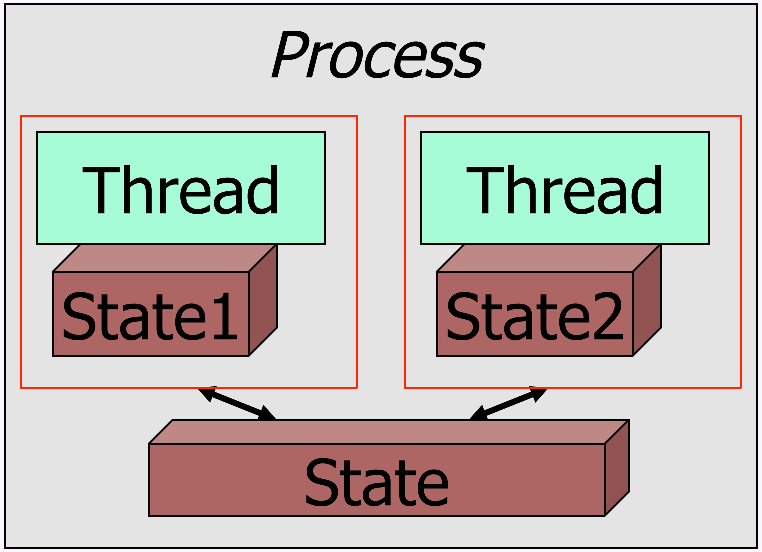


Aside: Abstractions of concurrency

- 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

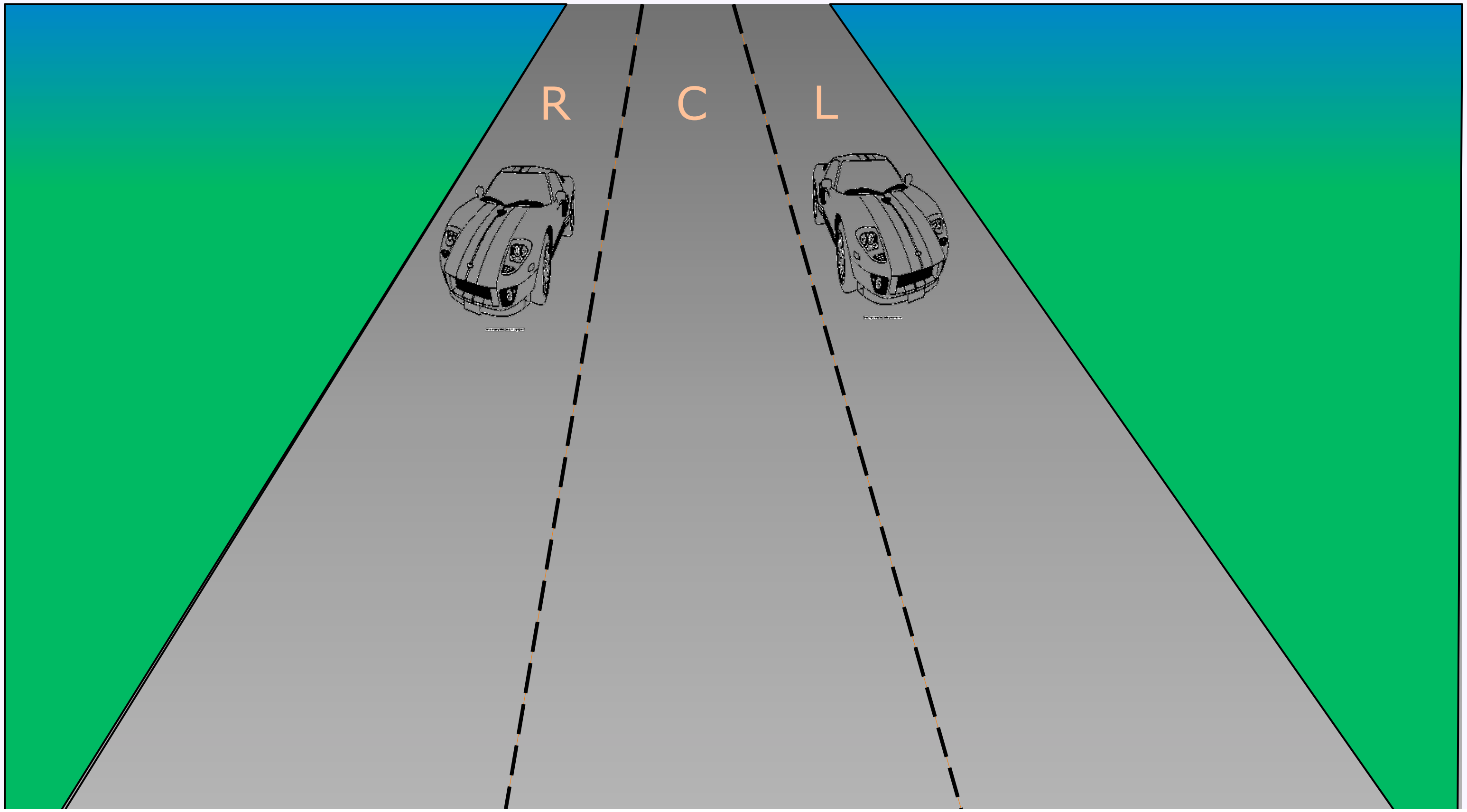
2B. Increment data(41) by 1 -> 42

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 ?**
    2. **Give $30 to *Bill***
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- **If *Alice* starts with $40, can *Bob* and *Bill* both get $30?**

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- **If *Alice* starts with $40, can *Bob* and *Bill* both get $30?**

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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int i = 7;
```

Thread A:

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- What are the possible values for `ans`?

`i:` **00000…00000111**

⋮

`i:` **00000…00101010**

Some actions are atomic

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Thread A:

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Thread B:

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ans = i;
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- What are the possible values for `ans`?

```
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:

- More concurrency