Lecture 03—Gustafson's Law, Concurrency vs Parallelism

ECE 459: Programming for Performance

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Multiprocessing in Three Acts

Act 1: **Attack of the Clones**
(symmetric multiprocessing systems)

Act 2: **The Empire Strikes Back**
(Amdahl's Law)

Act 3: **A New Hope**
(Gustafson's Law)

Amdahl's Law Generalization

The program may have many parts, each of which we can tune to a different degree.

Let's generalize Amdahl's Law.

$f_1, f_2, \ldots, f_n$: fraction of time in part n
$S_{f_1}, S_{f_n}, \ldots, S_{f_n}$: speedup for part n

$$\textbf{\textit{speedup}} = \frac{1}{\frac{f_1}{S_{f_1}} + \frac{f_2}{S_{f_2}} + \ldots + \frac{f_n}{S_{f_n}}}$$

Application (1)

Consider a program with 4 parts in the following scenario:

		Speedup	
Part	Fraction of Runtime	Option 1	Option 2
1	0.55	1	2
2	0.25	5	1
3	0.15	3	1
4	0.05	10	1

We can implement either Option 1 or Option 2.
Which option is better?

Application (2)

"Plug and chug" the numbers:

Option 1

$$\mathit{speedup} = \frac{1}{0.55 + \frac{0.25}{5} + \frac{0.15}{3} + \frac{0.05}{5}} = 1.53$$

Option 2

$$\mathit{speedup} = \frac{1}{\frac{0.55}{2} + 0.45} = 1.38$$

Empirically estimating parallel speedup P

Useful to know, don't have to commit to memory:

$$P_{\text{estimated}} = \frac{\frac{1}{speedup} - 1}{\frac{1}{N} - 1}$$

- Quick way to guess the fraction of parallel code
- Use $P_{\text{estimated}}$ to predict speedup for a different number of processors

Summary of Amdahl’s Law

Important to focus on the part of the program with most impact.

Amdahl’s Law:

- estimates perfect performance gains from parallelization (under assumptions); but,
- only applies to solving a **fixed problem size** in the shortest possible period of time

Gustafson's Law: Formulation

n: problem size
$S(n)$: fraction of serial runtime for a parallel execution
$P(n)$: fraction of parallel runtime for a parallel execution

$$\begin{aligned} T_p &= S(n) + P(n) = 1 \\ T_s &= S(n) + N \cdot P(n) \end{aligned}$$

$$speedup = \frac{T_s}{T_p}$$

Gustafson's Law

$$speedup = S(n) + N \cdot P(n)$$

Assuming the fraction of runtime in serial part decreases as n increases, the speedup approaches N.

- Yes! Large problems can be efficiently parallelized. (Ask Google.)

Driving Metaphor

Amdahl's Law
Suppose you're travelling between 2 cities 90 km apart. If you travel for an hour at a constant speed less than 90 km/h, your average will never equal 90 km/h, even if you energize after that hour.

Gustafson's Law
Suppose you've been travelling at a constant speed less than 90 km/h. Given enough distance, you can bring your average up to 90 km/h.

Part II

Parallelism versus Concurrency

Parallelism versus Concurrency

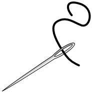
Parallelism
Two or more tasks are **parallel**
if they are running at the same time.
Main goal: run tasks as fast as possible.
Main concern: **dependencies**.

Concurrency
Two or more tasks are **concurrent**
if the ordering of the two tasks is not predetermined.
Main concern: **synchronization**.

Part III

Threads

Threads



- What are they?
- How do operating systems implement them?
- How can we leverage them?

Processes versus Threads

Process
An instance of a computer program that contains program code and its:

- Own address space / virtual memory;
- Own stack / registers;
- Own resources (file handles, etc.).

Thread
“Lightweight processes”.
In most cases, a thread is contained within a process.

- Same address space as parent process
  - Shares access to code and variables with parent.
- Own stack / registers
- Own thread-specific data

Software and Hardware Threads

Software Thread:
What you program with (e.g. with `pthread_create()` or `std::thread()`).

Corresponds to a stream of instructions executed by the processor.

On a single-core, single-processor machine, someone has to multiplex the CPU to execute multiple threads concurrently; only one thread runs at a time.

Hardware Thread:
Corresponds to virtual (or real) CPUs in a system. Also known as strands.

Operating system must multiplex software threads onto hardware threads, but can execute more than one software thread at once.

Thread Model—1:1 (Kernel-level Threading)

Simplest possible threading implementation.

The kernel schedules threads on different processors;

- NB: Kernel involvement required to take advantage of a multicore system.

Context switching involves system call overhead.

Used by Win32, POSIX threads for Windows and Linux.

Allows concurrency and parallelism.

Thread Model—N:1 (User-level Threading)

All application threads map to a single kernel thread.

Quick context switches, no need for system call.

Cannot use multiple processors, only for concurrency.

- Why would you use user threads?

Used by GNU Portable Threads.

Thread Model—M:N (Hybrid Threading)

Map *M* application threads to *N* kernel threads.

A compromise between the previous two models.

Allows quick context switches and the use of multiple processors.

Requires increased complexity:

- Both library and kernel must schedule.
- Schedulers may not coordinate well together.
- Increases likelihood of priority inversion
  (recall from Operating Systems).

Used by Windows 7 threads.

Live Coding Demo: Deducing the Thread Model

`time`, `top`, and `perf stat` all let you figure this out.