Lecture 17 — Critical Paths, Data & Task Parallelism

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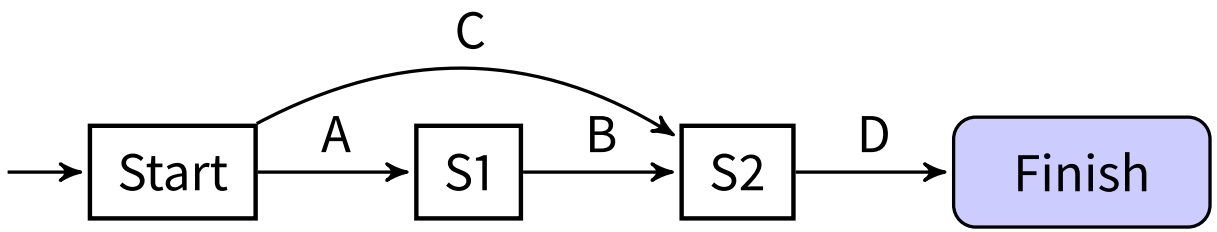
Critical Paths

Should be familiar with critcal paths from other courses (Gantt charts).

Consider the following diagram (edges are tasks):



- B depends on A, C has no dependencies, and D depends on B and C.
- Can execute A-then-B in parallel with C.
- Keep dependencies in mind when calculating speedups for more complex programs.

Data and Task Parallelism

Data parallelism is performing *the same* operations on different input.
Example: doubling all elements of an array.

Task parallelism is performing *different* operations on different input.

Example: playing a video file: one thread decompresses frames, another renders.

Data Parallelism: Single Instruction, Multiple Data

We'll discuss SIMD in more detail later. An overview:

- You can load a bunch of data and perform arithmetic.
- Intructions process multiple data items simultaneously. (Exact number is hardware-dependent).

For x86-class CPUs, MMX and SSE extensions provide SIMD instructions.

SIMD Example

Consider the following code:

```
void vadd(double * restrict a, double * restrict b,
          int count) {
  for (int i = 0; i < count; i++)
    a[i] += b[i];
}
```

In this scenario, we have a regular operation over block data.

We could use threads, but we'll use SIMD.

SIMD Example—Assembly without SIMD

If we compile this without SIMD instructions on a 32-bit x86, (flags `-m32 -march=i386 -S`) we might get this:

```
loop:
  fldl  (%edx)
  faddl (%ecx)
  fstpl (%edx)
  addl  8, %edx
  addl  8, %ecx
  addl  1, %esi
  cmp   %eax, %esi
  jle   loop
```

Just loads, adds, writes and increments.

SIMD Example—Assembly with SIMD

Instead, compiling to SIMD instructions
(`-m32 -mfpmath=sse -march=prescott`) gives:

```
loop:
   movupd  (%edx),%xmm0
   movupd  (%ecx),%xmm1
   addpd   %xmm1,%xmm0
   movpd   %xmm0,(%edx)
   addl    16,%edx
   addl    16,%ecx
   addl    2,%esi
   cmp     %eax,%esi
   jle     loop
```

- Now processing two elements at a time on the same core.
- Also, no need for stack-based x87 code.

SIMD Overview

- Operations *packed*: operate on multiple data elements at the same time.
- On modern 64-bit CPUs, SSE has 16 128-bit registers.
- Very good if your data can be *vectorized* and performs math.
- Usual application: image/video processing.
- We'll see more SIMD as we get into GPU programming: GPUs excel at these types of applications.

Task-Based Patterns: Overview

- We'll now look at thread and process-based parallelization.
- Although threads and processes differ, we don't care for now.

Pattern 1: Multiple Independent Tasks

Only useful to maximize system utilization.

- Run multiple tasks on the same system
  (e.g. database and web server).

  If one is memory-bound and the other is I/O-bound, for example, you'll get maximum utilization out of your resources.

  Example: cloud computing, each task is independent and can tasks can spread themselves over different nodes.

- Performance can increase linearly with the number of threads.

Pattern 2: Multiple Loosely-Coupled Tasks

Tasks aren't quite independent, so there needs to be some inter-task communication (but not much).

- Communication might be from the tasks to a controller or status monitor.

Refactoring an application can help with latency.
For instance: split off the CPU-intensive computations into a separate thread—your application may respond more quickly.

Example: A program (1) receives/forwards packets and (2) logs them. You can split these two tasks into two threads, so you can still receive/forward while waiting for disk. This will increase the throughput of the system.

Pattern 3: Multiple Copies of the Same Task

Variant of multiple independent tasks: run multiple copies of the same task (probably on different data).

- No communcation between different copies.

Again, performance should increase linearly with number of tasks.

Example: In a rendering application, each thread can be responsible for a frame (gain throughput; same latency).

Pattern 4: Single Task, Multiple Threads

Classic vision of “parallelization”.

Example: Distribute array processing over multiple threads—each thread computes results for a subset of the array.

- Can decrease latency (and increase throughput), as we saw with Amdahl’s Law.
- Communication can be a problem, if the data is not nicely partitioned.
- Most common implementation is just creating threads and joining them, combining all results at the join.

Pattern 5: Pipeline of Tasks

Seen briefly in computer architecture.

- Use multiple stages; each thread handles a stage.

  Example: a program that handles network packets: (1) accepts packets, (2) processes them, and (3) re-transmits them. Could set up the threads such that each packet goes through the threads.

- Improves throughput; may increase latency as there's communication between threads.

- In the best case, you'll have a linear speedup.

  Rare, since the runtime of the stages will vary, and the slow one will be the bottleneck (but you could have 2 instances of the slow stage).

Pattern 6: Client-Server

To execute a large computation, the server supplies work to many clients—as many as request it.

Client computes results and returns them to the server.

Examples: botnets, `SETI@Home`, GUI application (backend acts as the server).

Server can arbitrate access to shared resources (such as network access) by storing the requests and sending them out.

- Parallelism is somewhere between single task, multiple threads and multiple loosely-coupled tasks

Pattern 7: Producer-Consumer

Variant on the pipeline and client-server models.
Producer generates work, and consumer performs work.

Example: producer which generates rendered frames; consumer which orders these frames and writes them to disk.

Any number of producers and consumers.

- This approach can improve throughput and also reduces design complexity

Combining Strategies

Most problems don't fit into one category, so it's often best to combine strategies.

For instance, you might often start with a pipeline, and then use multiple threads in a particular pipeline stage to handle one piece of data.

Tip: estimate to see what divisions of strategies would work best (might have to do more iterations of Amdahl's law depending on the amount of strategies you can use).

Midterm Questions from 2011 (1)

For each of the following situations, **name an appropriate parallelization pattern and the granularity at which you would apply it, explain the necessary communication, and explain why your pattern is appropriate**.

- build system, e.g. parallel make
- optical character recognition system

Midterm Questions from 2011 (1)

For each of the following situations, **name an appropriate parallelization pattern and the granularity at which you would apply it, explain the necessary communication, and explain why your pattern is appropriate**.

- build system, e.g. parallel make
  - Multiple independent tasks, at a per-file granularity
- optical character recognition system
  - Pipeline of tasks
  - 2 tasks - finding characters and analyzing them

Midterm Questions from 2011 (2)

Give a concrete example where you would use the following parallelization patterns. **Explain** the granularity at which you'd apply the pattern.

- single task, multiple threads:
- producer-consumer (no rendering frames, please):

Midterm Questions from 2011 (2)

Give a concrete example where you would use the following parallelization patterns. **Explain** the granularity at which you'd apply the pattern.

- single task, multiple threads:
  - Computation of a mathematical function with independent sub-formulas.
- producer-consumer (no rendering frames, please):
  - Processing of stock-market data: a server might generate raw financial data (quotes) for a particular security. The server would be the producer. Several clients (or consumers) may take the raw data and use them in different ways, e.g. by computing means, generating charts, etc.

How To Parallelize Code: Strategy

Four-step outline:

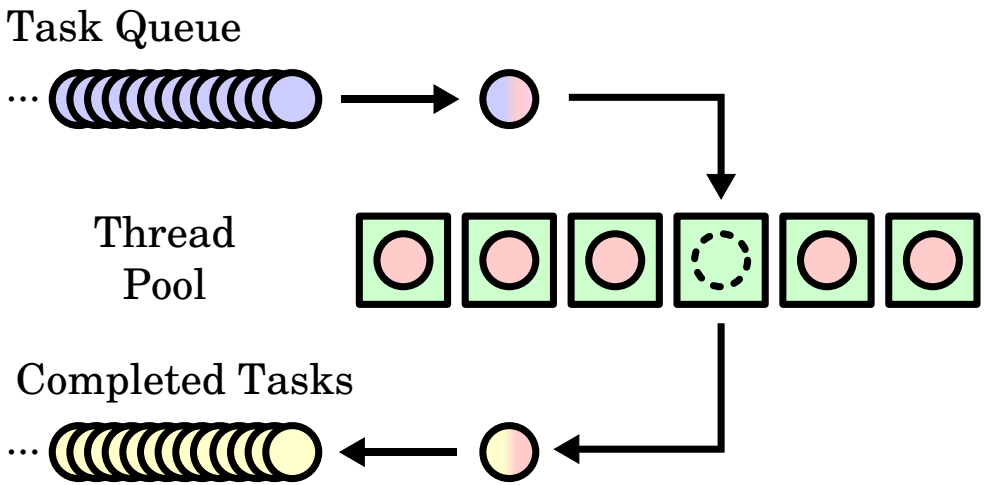
1. Profile the code.
2. Look at hotspots; find and optimize dependencies; parallelize dependency chains; change the algorithm if you can.
3. Estimate benefits.
4. If not good enough, step back and try higher level of abstraction.

Always try to minimize synchronization.

Low-level Implementation Tactic: Thread Pools

Instead of creating threads, destroying them and recreating them, you can use a thread pool.

- It creates *n* threads; you just `push` work onto them.



- Only question is: How many threads should you create? (Experiment to find out).
- Implementation from GLib: `GThreadPool`.