Lecture 9: Concurrent Programming in the Real World

(High-Performance Computing, Data Center, and Human-Computer Interaction)

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COP 4610 Operating Systems
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Outline

- High-Performance computing (HPC)
- Data Center
- Human-Computer Interaction (HCI)

Recap: Concurrent Programming in HPC

- The World's Most Expensive Sofa
  - The First Supercomputer (1976)
  - Single-processor system
  - 138 million FLOPs (Floating Point Operations per Second)
    - 40 times faster than IBM 370 at the time
    - Slightly better than embedded chips today
- Processed large data sets with one instruction

First Supercomputer (CRAY-1 from Los Alamos National Laboratory in 1976)

Recap: Features of HPC

HPC

"A technology that harnesses the power of supercomputers or computer clusters to solve complex problems requiring massive computation." (IBM)

- Computation-Centric
  - System Simulation: Weather forecasting, energy, molecular biology
  - Artificial Intelligence: Neural network training
  - Mining: Pure hash computation
  - TOP 500 (**https://www.top500.org/**)
    - 1st: Frontier (8, 699,904 cores, 1206 PFLOS)

Main Challenges of HPC

- How to Break Down Computation Tasks?
  - Computation Tasks need to be easy to parallelize
  - Task decomposition happens on two levels: machine and thread
  - Parallel and Distributed Computation: Numerical Methods

- **Independent Threads:**
  - Each thread executes its own task without needing to communicate with others
  - Useful for tasks that can be easily parallelized without shared data
  - Example: Performing different calculations on different parts of a dataset

Challenges of Breaking Down Computation Tasks

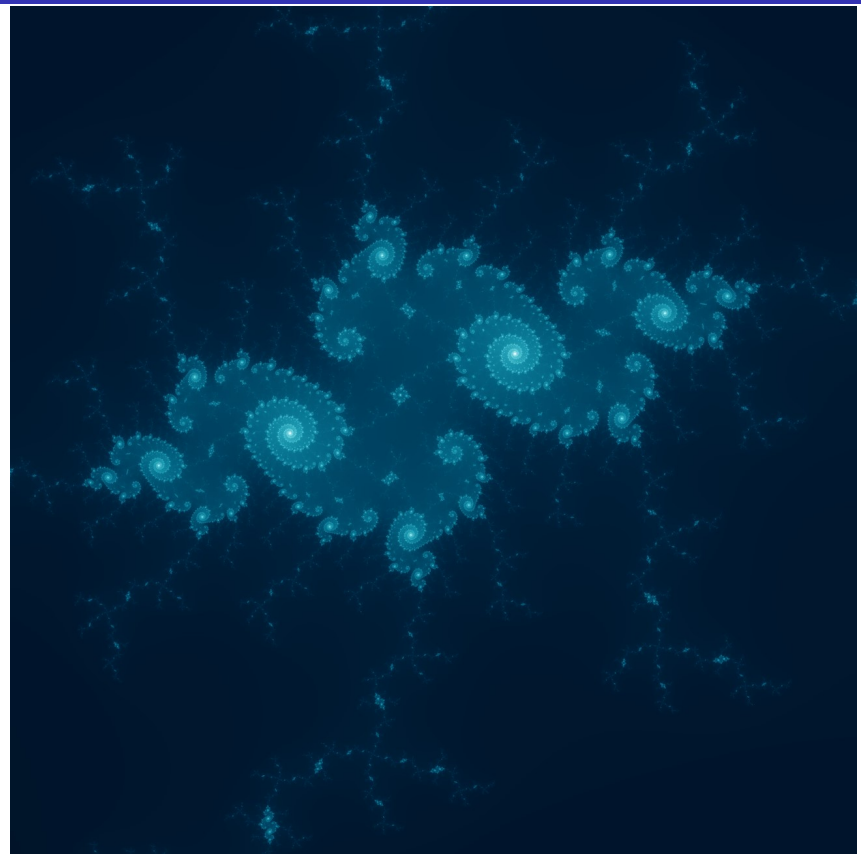
- Large tasks cannot be accomplished without communication and shared memory between threads.
- As calculations progress, tasks often require data sharing or synchronization, necessitating thread communication.
- The complexity of parallelism can be more challenging than other application scenarios.

- **Cooperating Threads:**
  - Threads need to communicate or synchronize to share data or resources
  - Require careful management

- **Tools for Managing Communication:**
  - **MPI:** Manages message-passing between distributed threads or nodes
  - **OpenMP:** Handles shared memory parallel programming, synchronizing threads that access shared data

Recap: Example: Mandelbrot Set

- $Z_{n+1}^2 = Z_n^2 + C$
- Each point in the Mandelbrot set iterates independently and is only influenced by its complex coordinate.
- Link of Code: **Mandelbrot Set Code**



- While the number of cores is not the only factor, it is the most critical factor for determining thread execution efficiency.
- Core count helps estimate the system's computational capacity and parallel processing capabilities.
- Therefore, it is a key factor in HPC.

Recap: Concurrent Programming in Data Centers

Google Data Center

Recap: Features of Data Center

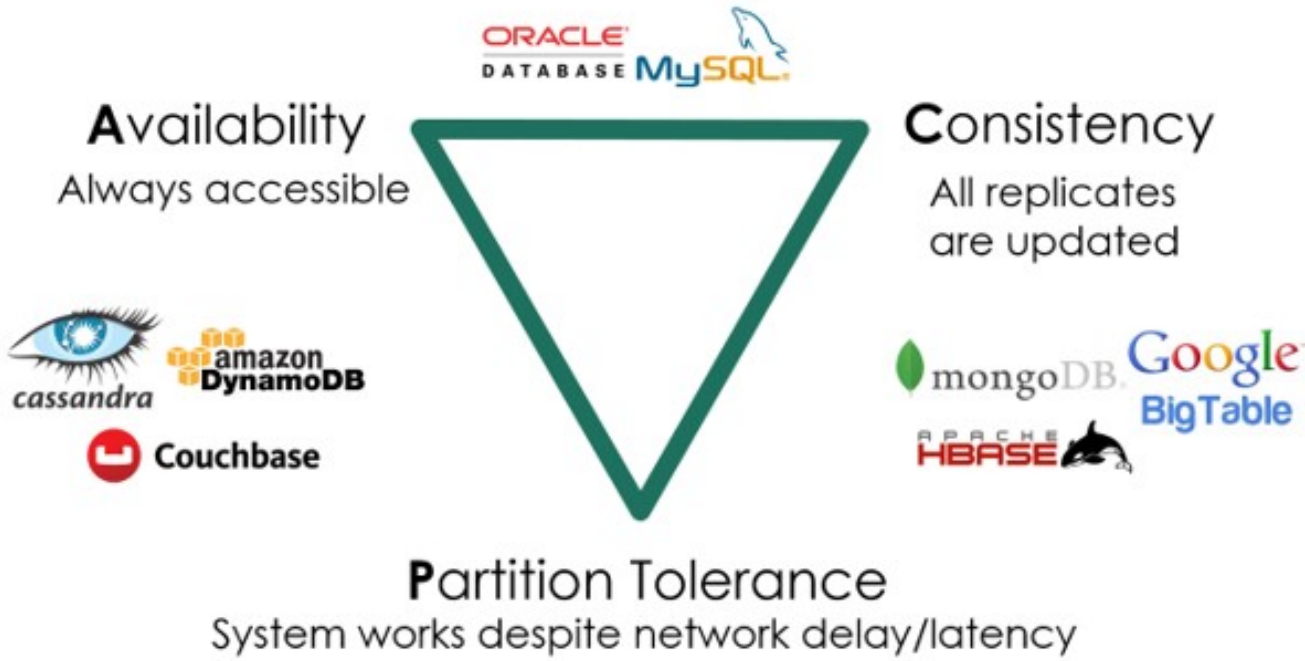
HPC

"A network of computing and storage resources that enable the delivery of shared applications and data." (CISCO)

- Data-Centric (Storage-Focused) Approach
  - Originated from internet search (Google), social networks (Facebook/Twitter)
  - Powers various internet applications: Gaming/Cloud Storage/ WeChat/Alipay/...
- The Importance of Algorithms/Systems for HPC and Data Centers
  - You manage 1,000,000 servers
  - A 1% improvement in an algorithm or implementation can save 10,000 servers

Recap: Main Challenges of Data Center

- Serving massive, geographically distributed requests
- Data must remain consistent (Consistency)
- Services must always be available (Availability)
    - Must tolerate machine failures (Partition Tolerance)



We foucus on a single machine

How to Maximize Parallel Request Handling with a Single Machine

- Key Metrics: QPS, Tail Latency, ...

Maximizing Parallel Request Handling: Threads

Advantages:

- True parallelism with multiple cores, enabling multiple execution flows.
- OS-level scheduling, allowing independent tasks to be managed efficiently by the operating system.
- Well-supported by most programming languages and operating systems.

Disadvantages:

- Higher overhead due to system calls and context switching.
- Limited by the number of cores, potentially leading to contention and inefficiencies with too many threads.
- Memory overhead due to thread stacks and system resources.

- Link of Code: **Thread Example Code**

Maximizing Parallel Request Handling: Coroutines

Advantages:

- More lightweight than threads, as they don't require system calls or context switches.
- Allow cooperative multitasking, reducing overhead compared to threads.
- Efficient for I/O-bound tasks as they can pause and resume without blocking other tasks.

Disadvantages:

- No true parallelism; all coroutines run on a single thread, limited by CPU core availability.
- Requires manual yielding and may lead to complex code management.
- Less well-supported across some programming languages compared to threads.

Why Coroutines Don't Require Context Switching

No Kernel Involvement:

- Thread context switching requires the OS to save and restore CPU registers, stack, and other states.
- Coroutines are scheduled in user space, not by the operating system kernel.
- Switching between coroutines happens entirely in user code, eliminating the need for kernel-level context switching as seen in threads.
  - The programmer explicitly controls when to yield execution (e.g., through 'await' or 'yield'), avoiding frequent kernel-level switches.

- Link of Code: **Coroutine Example Code**

Maximizing Parallel Request Handling: Go

Goroutines = Threads + Coroutines

Advantages:

- Goroutines are extremely lightweight and managed by Go's runtime, with low overhead.
- Automatic scheduling of goroutines by Go runtime, allowing them to run in parallel across multiple cores.
  - Near 100% performance efficiency in utilizing CPU resources
- Excellent for building high-concurrency systems with minimal developer management.

Disadvantages:

- Go runtime's scheduling decisions are opaque, making it harder to control execution flow.
- Debugging and profiling goroutines can be more difficult due to their lightweight nature and runtime control.
- Not available in all languages, limited to the Go ecosystem.

Why Goroutines = Threads + Coroutines?

- **When a Goroutine encounters a blocking system call:**
  - Go runtime automatically converts blocking system calls (e.g., file I/O) into non-blocking operations.
  - Go runtime moves the Goroutine off the current thread and schedules another Goroutine to continue execution.
  - This ensures that no Goroutine blocks the entire system, maximizing concurrency.

- Link of Code: **Goroutine Example Code**

The Web 2.0 Era (1999)

- The Internet brought people closer together.
- ”Users were encouraged to provide content, rather than just viewing it.”
- You can even find early hints of ”Web 3.0”/Metaverse in this period.

What made Web 2.0 possible?

- Concurrent programming in browsers: Ajax (Asynchronous JavaScript + XML)
- HTML (DOM Tree) + CSS represented everything you could see.
  - JavaScript allowed dynamic changes to the DOM.
  - JavaScript also enabled connections between local machines and servers.

With that, you had the whole world at your fingertips!

Features and Challenges

Features:

- Not very complex
- Minimal computation required
  - The DOM tree is not too large (humans can't handle huge trees anyway)
  - The browser handles rendering the DOM tree for us
- Not too much I/O, just a few network requests

Challenges:

- Too many programmers, especially for beginners
- Expecting beginners to handle multithreading with shared memory would lead to a world full of buggy applications!

Solution: Single-Threaded + Event Model

Asynchronous with minimal but sufficient concurrency:

- Single thread, global event queue, sequential execution (run-to-complete)
- Time-consuming APIs (Timer, Ajax, etc.) return immediately
- When conditions are met, a new event is added to the queue

Example: Chained Ajax Calls

```
$.ajax( { url: 'https://xxx.yyy.zzz/login',
  success: function(resp) {
    $.ajax( { url: 'https://xxx.yyy.zzz/cart',
      success: function(resp) {
        // do something
      },
      error: function(req, status, err) { ... }
    }
  },
  error: function(req, status, err) { ... }
);
```

Solution: Asynchronous Event Model

Advantages:

- Concurrency model is greatly simplified
  - Function execution is atomic (no parallel execution, reducing the chance of concurrency bugs)
- APIs can still run in parallel
  - Suitable for web applications where most time is spent on rendering and network requests
  - JavaScript code only ”describes” the DOM Tree

Disadvantages:

- Callback hell (the infamous ”spaghetti code”)
- As seen in the previous example, nesting 5 levels deep makes the code nearly unmaintainable

Asynchronous Programming: Promise

Definition:

- The Promise object represents the eventual completion (or failure) of an asynchronous operation and its resulting value.

Promise: An Embedded Language for Describing Workflows

- **Chaining:**

```
loadScript("/article/promise-chaining/one.js")
  .then(script => loadScript("/article/promise-chaining/two.js"))
  .then(script => loadScript("/article/promise-chaining/three.js"))
  .then(script => {
    // scripts are loaded, we can use functions declared there
  })
  .catch(err => { ... });
```

- **Fork-join:**

```
a = new Promise((resolve, reject) => { resolve('A') });
b = new Promise((resolve, reject) => { resolve('B') });
c = new Promise((resolve, reject) => { resolve('C') });
Promise.all([a, b, c]).then(res => { console.log(res) });
```

Async-Await: Even Better

async function:

- Always returns a Promise object
- `async_func()` - fork
- `await promise` - join

```
A = async () => await $.ajax('/hello/a');
B = async () => await $.ajax('/hello/b');
C = async () => await $.ajax('/hello/c');

hello = async () => await Promise.all([A(), B(), C()]);

hello()
  .then(window.alert)
  .catch(res => { console.log('fetch failed!') });
```

Takeaways

- High-Performance Computing
  - Focus: Task Decomposition
  - Pattern: Producer-Consumer
  - Technologies: MPI / OpenMP
- Data Centers
  - Focus: System Calls
  - Pattern: Threads-Coroutines
  - Technologies: Goroutine
- Human-Computer Interaction
  - Focus: Usability
  - Pattern: Event-Stream Graph
  - Technologies: Promise.