Multi-threaded Performance Pitfalls

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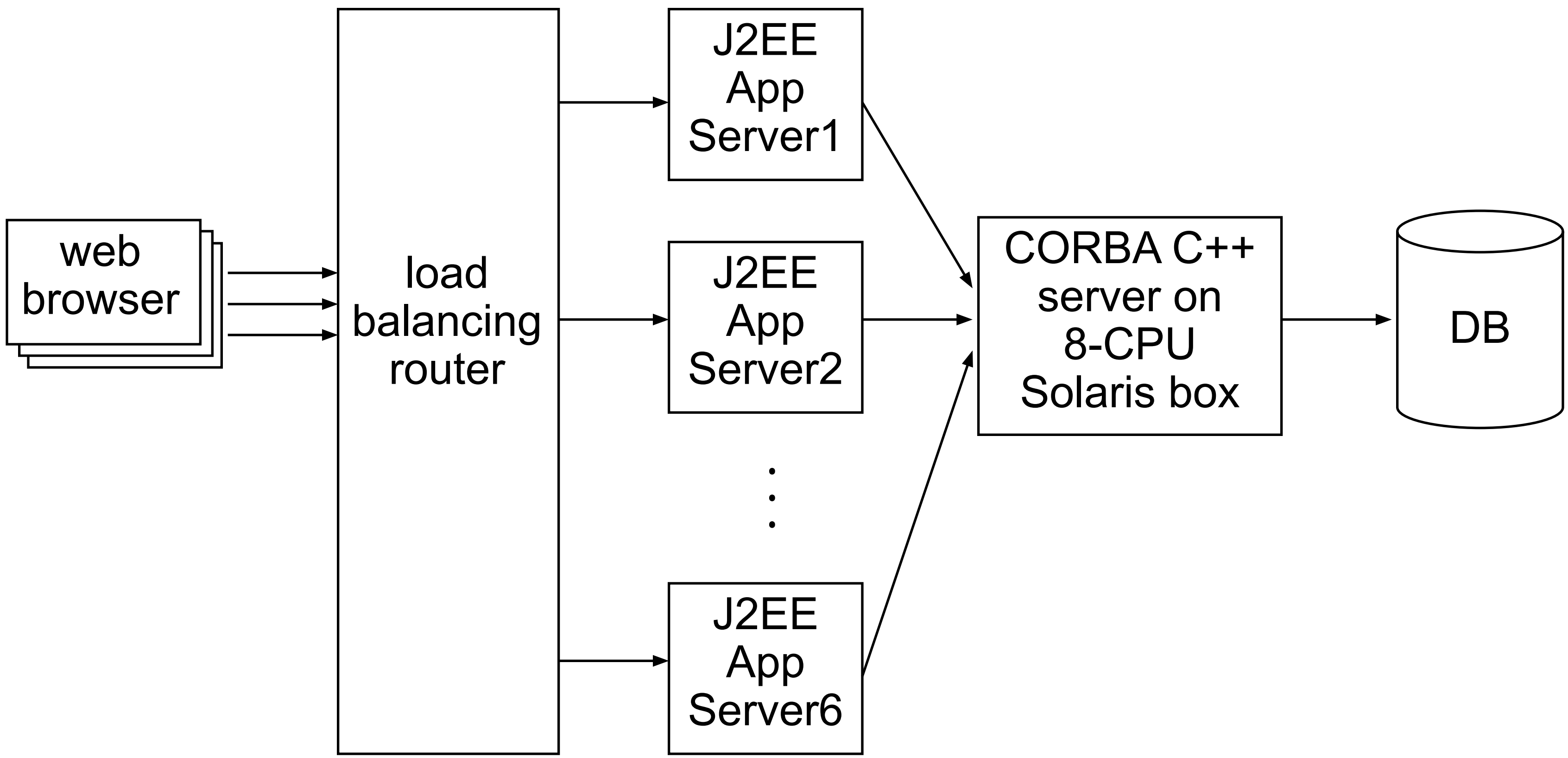
Purpose of this presentation

- Some issues in multi-threading are counter-intuitive
- Ignorance of these issues can result in poor performance
  - Performance can actually get *worse* when you add more CPUs
- This presentation explains the counter-intuitive issues

1. A case study

Architectural diagram



Architectural notes

- The customer felt J2EE was slower than CORBA/C++
- So, the architecture had:
  - Multiple J2EE App Servers acting as clients to…
  - Just one CORBA/C++ server that ran on an 8-CPU Solaris box
- The customer assumed the CORBA/C++ server “should be able to cope with the load”

Strange problems were observed

- Throughput of the CORBA server *decreased* as the number of CPUs increased
  - It ran fastest on 1 CPU
  - It ran slower but “fast enough” with moderate load on 4 CPUs (development machines)
  - It ran very slowly on 8 CPUs (production machine)
- The CORBA server ran faster if a thread pool limit was imposed
- Under a high load in production:
  - Most requests were processed in < 0.3 second
  - But some took up to a minute to be processed
  - A few took up to 30 minutes to be processed
- This is *not* what you hope to see

2. Analysis of the problems

What went wrong?

- Investigation showed that scalability problems were caused by a combination of:
  - Cache consistency in multi-CPU machines
  - Unfair mutex wakeup semantics
- These issues are discussed in the following slides
- Another issue contributed (slightly) to scalability problems:
  - Bottlenecks in application code
  - A discussion of this is outside the scope of this presentation

Cache consistency

- RAM access is much slower than speed of CPU
  - Solution: high-speed cache memory sits between CPU and RAM
- Cache memory works great:
  - In a single-CPU machine
  - In a multi-CPU machine if the threads of a process are “bound” to a CPU
- Cache memory can backfire if the threads in a program are spread over all the CPUs:
  - Each CPU has a separate cache
  - Cache consistency protocol require cache flushes to RAM (cache consistency protocol is driven by calls to `lock()` and `unlock()`)

Cache consistency (cont')

- Overhead of cache consistency protocols worsens as:
  - Overhead of a cache synchronization increases (this increases as the number of CPUs increase)
  - Frequency of cache synchronization increases (this increases with the rate of mutex `lock()` and `unlock()` calls)
- Lessons:
  - Increasing number of CPUs can *decrease* performance of a server
  - Work around this by:
    - Having multiple server processes instead of just one
    - Binding each process to a CPU (avoids need for cache synchronization)
  - Try to minimize need for mutex `lock()` and `unlock()` in application
    - Note: `malloc()`/`free()`, and `new`/`delete` use a mutex

Unfair mutex wakeup semantics

- A mutex does *not* guarantee First In First Out (FIFO) wakeup semantics
  - To do so would prevent two important optimizations (discussed on the following slides)
- Instead, a mutex provides:
  - Unfair wakeup semantics
    - Can cause *temporary* starvation of a thread
    - But guarantees to avoid *infinite* starvation
  - High speed `lock()` and `unlock()`

Unfair mutex wakeup semantics (cont')

- Why does a mutex *not* provide fair wakeup semantics?
- Because most of the time, speed matter more than fairness
  - When FIFO wakeup semantics are required, developers can write a `FIFOMutex` class and take a performance hit

Mutex optimization 1

- Pseudo-code:

```
void lock()
{
    if (rand() % 100) < 98) {
        add thread to head of list; // LIFO wakeup
    } else {
        add thread to tail of list; // FIFO wakeup
    }
}
```

- Notes:
  - Last In First Out (LIFO) wakeup increases likelihood of cache hits for the woken-up thread (avoids expense of cache misses)
  - Occasionally putting a thread at the tail of the queue prevents *infinite* starvation

Mutex optimization 2

- Assume several threads concurrently execute the following code:

```
for (i = 0; i < 1000; i++) {
    lock(a_mutex);
    process(data[i]);
    unlock(a_mutex);
}
```

- A thread context switch is (relatively) expensive
  - Context switching on *every* `unlock()` would add a lot of overhead
- Solution (this is an unfair optimization):
  - Defer context switches until the end of the current thread's time slice
  - Current thread can *repeatedly* `lock()` and `unlock()` mutex in a single time slice

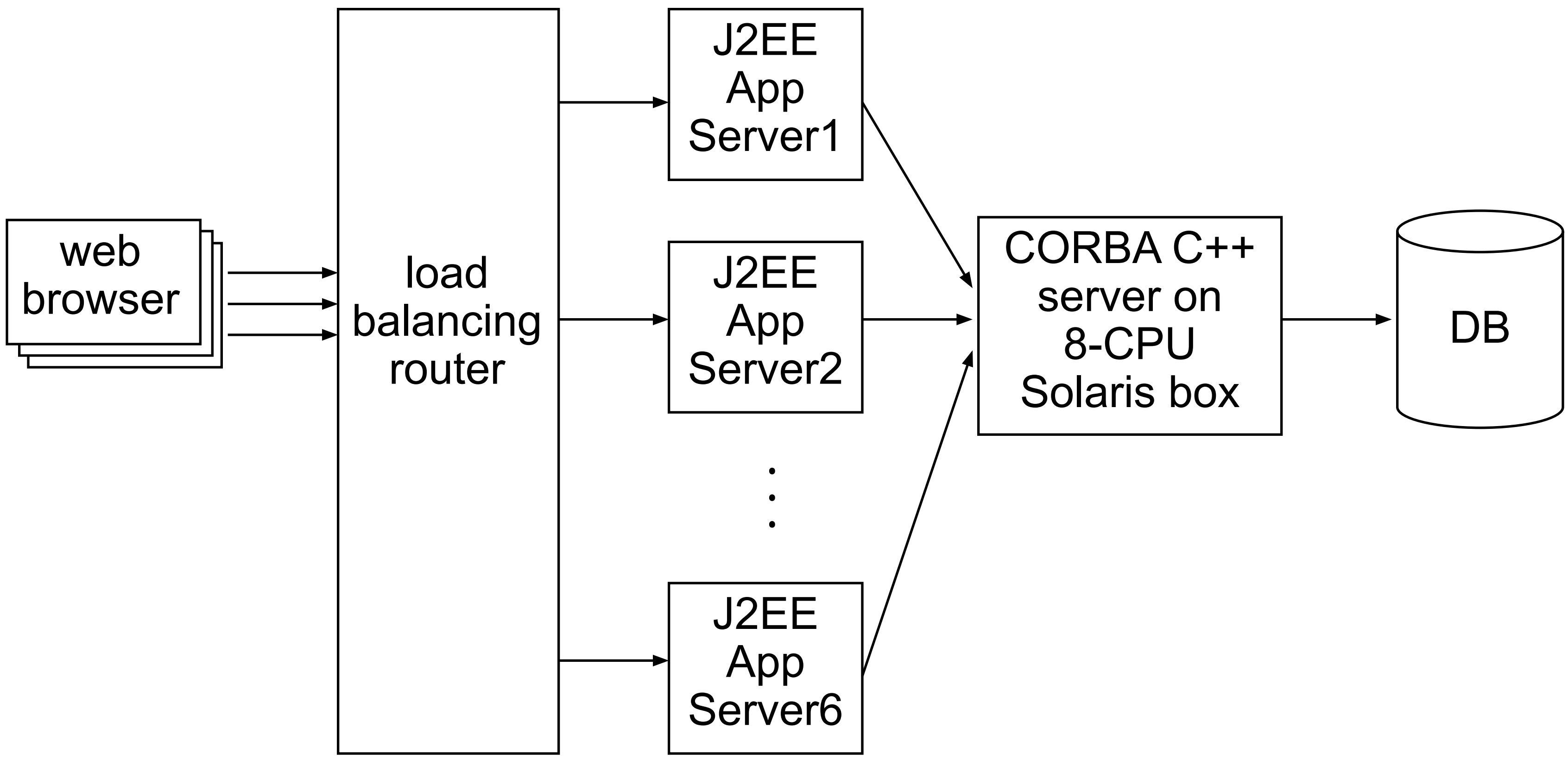
3. Improving Throughput

Improving throughput

- 20X increase in throughput was obtained by combination of:
  - Limiting size of the CORBA server's thread pool
    - This Decreased the maximum length of the mutex wakeup queue
    - Which decreased the maximum wakeup time
  - Using several server processes (each with a small thread pool) rather than one server process (with a very large thread pool)
  - Binding each server process to one CPU
    - This avoided the overhead of cache consistency
    - Binding was achieved with the `pbind` command on Solaris
    - Windows has an equivalent of process binding:
      - Use the `SetProcessAffinityMask()` system call
      - Or, in Task Manager, right click on a process and choose the menu option
        (this menu option is visible only if you have a multi-CPU machine)

4. Finishing up

Recap: architectural diagram



The case study is not an isolated incident

- The project's high-level architecture is quite common:
  - Multi-threaded clients communicate with a multi-threaded server
  - Server process is not "bound" to a single CPU
  - Server's thread pool size is unlimited
    (this is the default case in many middleware products)

- Likely that *many* projects have similar scalability problems:
  - But the system load is not high enough (yet) to trigger problems

- Problems are *not* specific to CORBA
  - They are independent of your choice of middleware technology

- Multi-core CPUs are becoming more common
  - So, expect to see these scalability issues occurring more frequently

Summary: important things to remember

- Recognize danger signs:
  - Performance drops as number of CPUs increases
  - Wide variation in response times with a high number of threads
- Good advice for multi-threaded servers:
  - Put a limit on the size of a server's thread pool
  - Have several server processes with a small number of threads instead of one process with many threads
  - Bind each a server process to a CPU