CASE STUDY OF SHARED-MEMORY PARALLELIZATION

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Agenda

- Shared Memory Review
- Performance implications of shared memory hardware
  - Data sharing
  - Contested accesses
- Performance implications of shared memory software
  - Data races
  - Deadlocks
  - Poor synchronization
  - Static thread scheduling
  - Scalability
  - Load imbalance
  - Oversubscription
  - Lock contention
Shared Memory Review
Performance Implications of Shared-Memory Hardware

- Modern CPUs have a shared address space for all the cores
- Need to maintain correctness, as different cores work on the same data
- Hardware protocols maintain coherency, but can have performance impacts

https://people.cs.pitt.edu/~xianeizhang/notes/cache.html
Performance Implications of Shared-Memory Hardware

- Metrics available in Intel® VTune™ Amplifier General Exploration
**Data Sharing**

**Why:** Sharing clean data (read sharing) among cores (at L2 level) has a penalty at least the first time due to coherency.

**What Now:** If this metric is highlighted for your hotspot, locate the source code line(s) that is generating HITs by viewing the source.

- Look for the MEM_LOAD_L3_HIT_RETIRED.XSNP_HIT_PS event which will tag to the next instruction after the one that generated the HIT.
- Use knowledge of the code to determine if real or false sharing is taking place. Make appropriate fixes:
  - For real sharing, reduce sharing requirements
  - For false sharing, pad variables to cache line boundaries
Contested Accesses

**Why:** Sharing modified data among cores (at L2 level) can raise the latency of data access

**What Now:** If this metric is highlighted for your hotspot, locate the source code line(s) that is generating HITMs by viewing the source.

- Look for the MEM_LOAD_L3_HIT RETIRED.XSNP_HITM_PS event which will tag to the next instruction after the one that generated the HITM.
- Use knowledge of the code to determine if real or false sharing is taking place. Make appropriate fixes:
  - For real sharing, reduce sharing requirements
  - For false sharing, pad variables to cache line boundaries
Performance Implications of Shared-Memory Software

- Data races
- Deadlocks
- Poor synchronization
- Static thread scheduling
- Scalability
- Load imbalance
- Oversubscription
- Lock contention
do {
    auto old_dst_dist = dst_data.load();
    auto new_dst_dist = src_data.load() + w;
    if (new_dst_dist < old_dst_dist) {
        dst_data = new_dst_dist;
        swapped = true;
    }
} while (!swapped);

Data Races - SSSP

Application may:
• Crash Immediately
• Hang
• Run but give incorrect results
• Run and give correct results
• Run correctly 99 times but crash once (usually once you ship it to customers)

Non-determinism is always a concern in parallel programming. It may depend on how the OS decides to schedule threads.
Data Races - SSSP

```cpp
do {
    auto old_dst_dist = dst_data.load();
    auto new_dst_dist = src_data.load() + w;
    if (new_dst_dist < old_dst_dist) {
        dst_data = new_dst_dist;
        swapped = true;
    }
} while (!swapped);
```

Shared variables unprotected

```cpp
do {
    auto old_dst_dist = dst_data.load();
    auto new_dst_dist = src_data.load() + w;
    if (new_dst_dist < old_dst_dist) {
        pthread_mutex_lock(&swap_mutex);
        dst_data = new_dst_dist;
        swapped = true;
        pthread_mutex_unlock(&swap_mutex);
    }
} while (!swapped);
```

Add a critical section
Threading Problems - Deadlock

```c
CRITICAL_SECTION cs1;
CRITICAL_SECTION cs2;
int x = 0;
int y = 0;
InitializeCriticalSection(&cs1); // Allocation Site (cs1)
InitializeCriticalSection(&cs2); // Allocation Site (cs2)
```

Thread #1

```c
EnterCriticalSection(&cs1);
x++;
EnterCriticalSection(&cs2);
y++;
LeaveCriticalSection(&cs2);
LeaveCriticalSection(&cs1);
```

Thread #2

```c
EnterCriticalSection(&cs2);
y++;
EnterCriticalSection(&cs1);
x++;
LeaveCriticalSection(&cs1);
LeaveCriticalSection(&cs2);
```

Deadlock

1. EnterCriticalSection(&cs1); in thread #1
2. EnterCriticalSection(&cs2); in thread #2
do {
    auto old_dst_dist = dst_data.load();
    auto new_dst_dist = src_data.load() + w;

    if (new_dst_dist < old_dst_dist) {
        pthread_mutex_lock(&swap_mutex);
        &dst_data = new_dst_dist;
        pthread_mutex_unlock(&swap_mutex);
    } else {
        swapped = true;
    }
} while (!swapped);
```cpp
do {
    auto old_dst_dist = dst_data.load();
    auto new_dst_dist = src_data.load() + w;

    if (new_dst_dist < old_dst_dist) {
        swapped =
        std::atomic_compare_exchange_weak(&dst_data, &old_dst_dist, new_dst_dist);
        changed |= swapped;
    } else {
        swapped = true;
    }
} while (!swapped);
```
do {
    auto old_dst_dist = dst_data.load();
    auto new_dst_dist = src_data.load() + w;

    if (new_dst_dist < old_dst_dist) {
        swapped = std::atomic_compare_exchange_weak(&dst_data,
           &old_dst_dist, new_dst_dist);
        changed |= swapped;
    } else {
        swapped = true;
    }
} while (!swapped);
Static Thread Scheduling - SSSP

Hardcoding thread counts or relying on inputs can have performance impacts

```c
src_node = std::atoi(argv[2]) - 1;
initialize_sssp();

#ifdef SP2018_CS377P_PARALLEL
num_threads = std::atoi(argv[3]);
#endif
compute_sssp();
```

* I know this was used to teach concepts

```c
NUM_THREADS = 4;
pthread_t threads[NUM_THREADS];
int rc;
long t;
int chunk = limit/NUM_THREADS;
for(t=0;t<NUM_THREADS;t++){
    range *r = new range();
```
Static Thread Scheduling - SSSP

Hardcoding thread counts or relying on inputs can have performance impacts.

```cpp
src_node = std::atoi(argv[2]) - 1;
initialize_sssp();

#ifdef SP2018_CS377P_PARALLEL
    num_threads = std::atoi(argv[3]);
#endif
compute_sssp();
```

*I know this was used to teach concepts*

...`NUM_THREADS = 4; NUM_THREADS = get_num_procs();`
```cpp
pthread_t threads[NUM_THREADS];
int rc;
long t;
int chunk = limit/NUM_THREADS;
for(t=0;t<NUM_THREADS;t++){
    range *r = new range();
}
```

Use dynamic processor identification or scalable runtime library like OpenMP or Threading Building Blocks

```cpp
#pragma omp parallel for
```

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Scalability is Not a Given - SSSP

- Elapsed Time: 22.947s
  - CPU Time: 21.470s
  - Total Thread Count: 3
  - Paused Time: 1.457s

- Elapsed Time: 15.791s
  - CPU Time: 25.830s
  - Total Thread Count: 4

- Elapsed Time: 10.978s
  - CPU Time: 30.200s
  - Total Thread Count: 6

- Elapsed Time: 7.239s
  - CPU Time: 34.140s
  - Total Thread Count: 10

- Elapsed Time: 6.124s
  - CPU Time: 49.720s
  - Total Thread Count: 18
  - Paused Time: 1.253s
Scalability is Not a Given - SSSP

**Strong Scaling** - Solution time scales with the number of processors for a fixed *total* problem size.

**Weak Scaling** - Solution time scales with the number of processors for a fixed *total* problem size *per processor* - i.e. scales if the problem size also scales.

**Serial Time** will always be a limiting factor as well.
Load Balancing

- Work should be divided among threads evenly
- What is even?
  - Loop Iterations? Elements to process?
  - Intelligent parallelism uses dynamic workload balancing
  - Work stealing and/or dynamic chunking

Should we divide work by subgraphs?
Load Balancing – Work Stealing

Worker thread

Task starting

Local task pool

Execution

Steal
Example – Calculating Prime Numbers

```c
int main(int argc, _TCHAR* argv[])
{
    DWORD msBegin = timeGetTime();

    #pragma omp parallel for
    for(int p = 3; p <= limit; p += 2) {
        if(IsPrime(p)) Tick();
    }
    DWORD msDuration = timeGetTime() - msBegin;

    printf("MS: %d\n", msDuration);
    printf("primes = %d\n", primes);
    return primes != correctCount;
}
```

- Is 7 prime?
- Is 76853341 prime?

Static Scheduling/Chunking:
- Check 1-10000
- Check 10001-20000
- Check 20001-30000
- ...
Example – Calculating Prime Numbers

```c
int _tmain(int argc, _TCHAR* argv[])
{
    DWORD msBegin = timeGetTime();

    #pragma omp parallel for
    for(int p = 3; p <= limit; p += 2) {
        if (IsPrime(p))Tick();
    }
    DWORD msDuration = timeGetTime() - msBegin;
    printf("MS: %d\n", msDuration);
    printf("primes = %d\n", primes);
    return primes != correctCount;
}
```
Example – Calculating Prime Numbers

```c
int _tmain(int argc, _TCHAR* argv[])
{
    DWORD msBegin = timeGetTime();
    #pragma omp parallel for schedule (dynamic, 1000)
    for(int p = 3; p <= limit; p += 2) {
        if (IsPrime(p)) Tick();
    }
    DWORD msDuration = timeGetTime() - msBegin;
    printf("MS: %d\n", msDuration);
    printf("primes = %d\n", primes);
    return primes != correctCount;
}
```

- **Switch to Dynamic Scheduling**
- **More Balanced Threads**

![CPU Usage Histogram](image)

- This histogram displays a percentage of the wall time the specific number of CPUs.
Oversubscription

Common Causes:
- Nested Parallelism
- Manual Threading
- Library Usage
Lock Contention

- Acquiring and releasing a lock isn't free – it has overhead
- Threads waiting for a lock also impacts performance
- How do we balance these?

Imagine an array that multiple threads read and write
Lock Contention

0 ... N

1 Shared Lock?

Dense lock contention and stalls
Lock Contention

Lots of locking overhead

What can we do?

- Adjust lock granularity
- Using lock free or thread safe data structures
  - `tbb::atomic<int> primes;`
  - `tbb::concurrent_vector<int> all_primes;`
- Local storage and reductions
Summary

• Programming for shared memory is difficult
• Correctness and performance issues are unique
• Issues are from hardware and software
  • Data sharing
  • Contested accesses
  • Deadlock
  • Data races
  • Poor synchronization
  • Static thread scheduling
  • Scalability
  • Load imbalance
  • Oversubscription
  • Lock contention
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