Parallel Computing

Part 2, Chapter 8

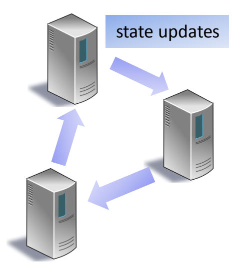
Roger Wattenhofer

Overview

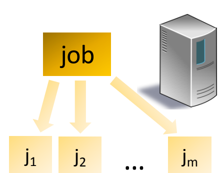
- Structure of a parallel computer
- Parallel Software for 16 cores (CPU)
- Parallel Software for 1,600 cores (GPU)

Programming Parallel Systems

- So far, we talked (mainly) about storage systems
  - Main question: How can we guarantee a consistent system state

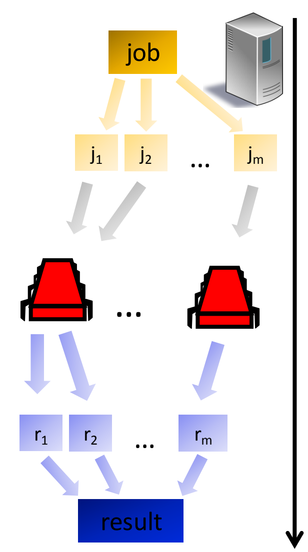


- Already desktop systems can be used for parallel computation
  - Distribute work load in the system!
  - How can we do this?
  - What's underneath the hood?



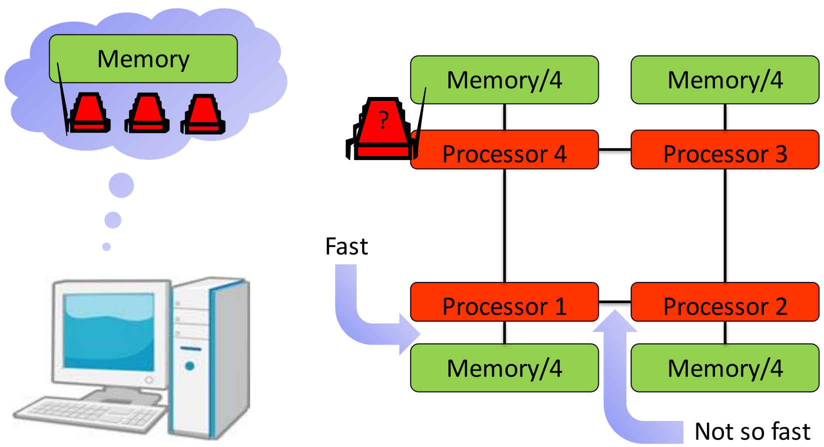
Programming Parallel Systems: Basic Idea

- Our model for parallel programming:
- A job is split into many small tasks
  - These tasks can be executed in parallel
- The tasks can be distributed
  - Each „worker thread“ may get many tasks
- The partial results may be merged
  - This is just another kind of "task"



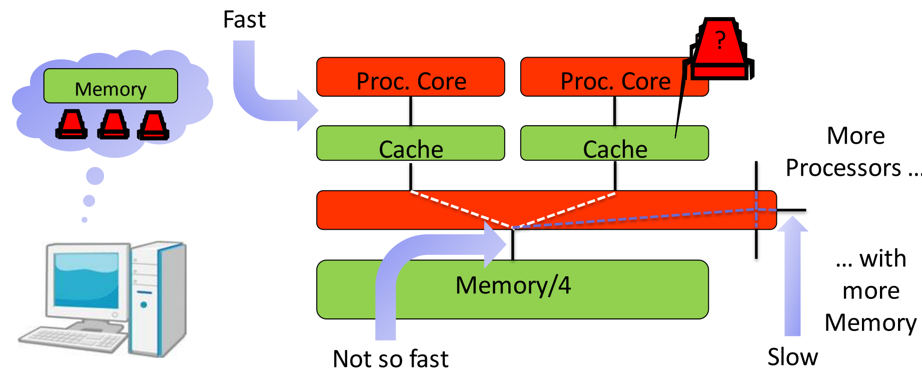
Programming Parallel Systems: Promise and Reality

Promise | **A Real Computer?**



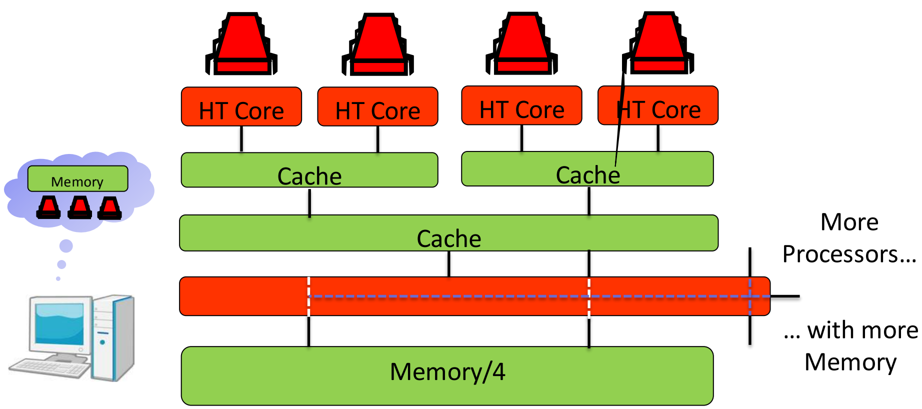
Programming Parallel Systems: Promise and Reality

Promise | **A Real Processor**



Programming Parallel Systems: Promise and Reality

Promise | **Intel Processor**



- Need to know your hardware for maximum efficiency
  - Cache Sizes, Topology & Bandwidth of Buses
  - Think: Data locality, (hidden!) communication cost

Programming Parallel Systems: A To-Do List

- We need to
  - **write code** for worker threads
  - **distribute** the threads to the cores
  - **split** the job into smaller tasks (how small?)
  - **assign** tasks to threads
  - **balance** the load on all threads
  - **collect** the (partial) results from the machines
  - **assembly** the results

- Should be fast as well, i.e., make use of **locality**
  - cache locality *and* prefer local memory over remote memory!
- The **complexity** of the program increases significantly!!!
- Solution?

OpenMP

- OpenMP is a specification developed by AMD, Cray, IBM, Intel, NVIDIA, …
  - Parallelization
  - Load balancing
  - Implicit use of locality
    - If you know what you are doing
  - All in one library!
- Not really a library, but a language-extension
  - C, C++, Fortran (still used in scientific computing)
- Supports Basic Parallel Constructs
  - Loops, basic reductions, tasks, …
  - Synchronization

OpenMP: An Example

```
std::vector<int> a(N);
std::vector<int> b(N);
```

a[i]*b[i]?

```
void sequential()
{
  for (int i = 0; i < N; i++)
    a[i] *= b[i];
}
```

- Split loop into tasks
- Distribute tasks to workers

```
void parallel()
{
#pragma omp parallel for
  for (int i = 0; i < N; i++)
    a[i] *= b[i];
}
```

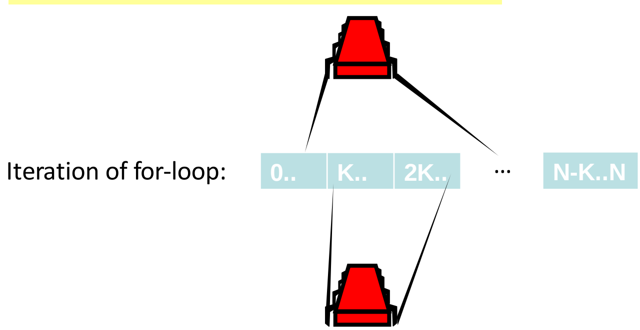
4 Procs x 4 Cores = 16 Threads
Speedup: 3.1x

Only 3.1x?

OpenMP: Under the Hood

```
void parallel()
{
#pragma omp parallel for
  for (int i = 0; i < N; i++)
    a[i] *= b[i];
}
```

When a worker is free:
grab the next available task
(block of iterations)



Where are the memory cells accessed in iteration i?

OpenMP: Digging Deeper

```
std::vector<int> a(N);
std::vector<int> b(N);
```

- Physical memory location depends on **Operating System**
- **Virtual** Memory presented as continuous block
  - **Physical** Memory may be scattered
  - A single **page** of virtual/physical memory cannot be scattered
  - Typical page sizes: 4KB, SuperPage: 4MB
- Many OSes
  - Explicitly: Offer system call to pin a page to a physical processor by hand
  - Implicitly: Pin virtual pages to processor that first accesses it
  - How is this done?

OpenMP: Static Scheduling

```
int *a, *b;
```

```
a = (int*)malloc(N*sizeof(int));
b = (int*)malloc(N*sizeof(int));
```

```
void fill()
{
#pragma omp parallel for schedule(static)
  for (int i = 0; i < N; ++i) {
    a[i] = a_value(i);
    b[i] = b_value(i);
  }
}
```

Chunk x is assigned to thread x mod num_threads

```
void parallel()
{
#pragma omp parallel for schedule(static)
  for (int i = 0; i < N; ++i)
    a[i] *= b[i];
}
```

4 Procs x 4 Cores = 16 Threads
Speedup: 6.7x

Only 6.7x?

Not Every Parallel Program is a for-loop

- Barely scratched the surface of OpenMP
  - Reductions

```
int sum = 0;
#pragma omp parallel for reduction(+:sum)
  for (int i = 0; i < N; i++) {
    sum += a[i] + b[i];
  }
```


Not Every Parallel Program is a for-loop

- Barely scratched the surface of OpenMP
  - Reductions
  - Arbitrary task types

```
cout<<"A ";
#pragma omp parallel
{
  #pragma omp single
  {
    #pragma omp task
    { cout<<"car "; }
    #pragma omp task
    { cout<<"race "; }


  }
}
cout<<endl;
```

A race car car race
(or)
A car car race race
(or…)

Not Every Parallel Program is a for-loop

- Barely scratched the surface of OpenMP
  - Reductions
  - Arbitrary task types
  - Synchronization primitives

```
cout<<"A ";
#pragma omp parallel
{
  #pragma omp single
  {
    #pragma omp task
    { cout<<"car "; }
    #pragma omp task
    { cout<<"race "; }
    #pragma omp taskwait
    cout<<"is fun to watch";
  }
}
cout<<endl;
```

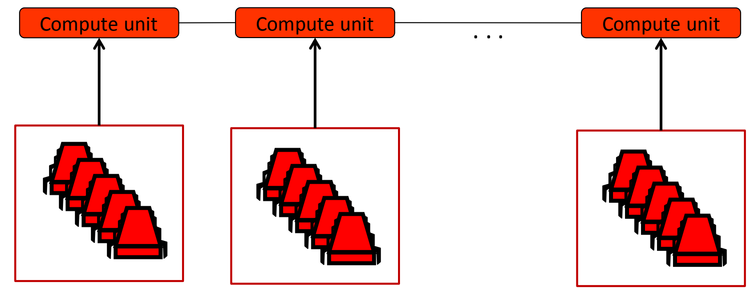
A car race is fun to watch
(or)
A race car is fun to watch

Not Every Parallel Program is a for-loop

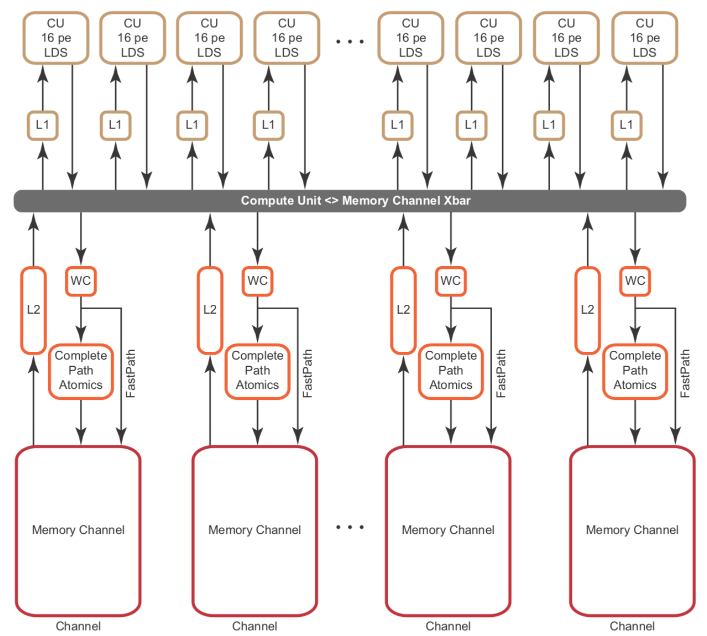
- Barely scratched the surface of OpenMP
  - Reductions
  - Arbitrary task types
  - Synchronization primitives
  - …
- Already a simple loop can be tricky
- Simple loops are everywhere!
  - Think: Vectors, Matrix Multiplication
  - Simple loops deserve their own hardware

Graphic Processing Unit (GPU)

- The complexity of the architecture increases further
- The GPU consists of compute units, each with multiple stream cores
  - As an example, AMD Radeon R9 290X has 2816 stream cores



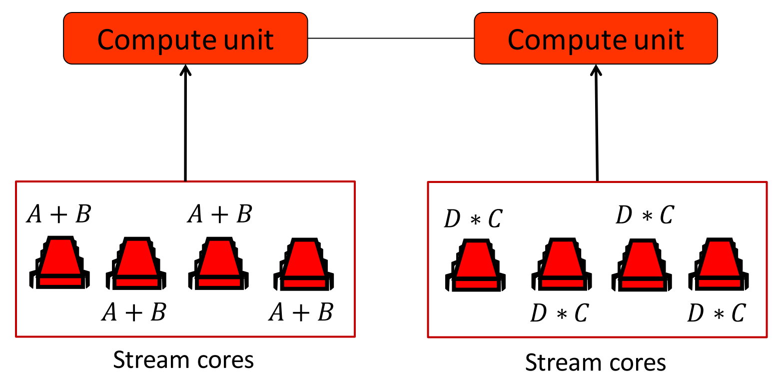
The Real Deal



Programming Guide
AMD Accelerated Parallel Processing
OpenCL TM

Graphic Processing Unit (GPU)

- Different compute units can do different things
- All stream cores execute the same instruction sequence
  - With separate local memories



- What is this good for?

Matrix Operations

- Matrix operations are the core of graphics computations
- For example, matrix multiplication can be highly parallelized
- Naive: $O(n^3)$ multiplications

		Core i	Core j		
9	0	4	1	5	0
9	1	3	1	1	4
1	0	4	6	0	7
2	1	0	0	0	0
0	0	0	1	0	0
0	0	1	1	1	0

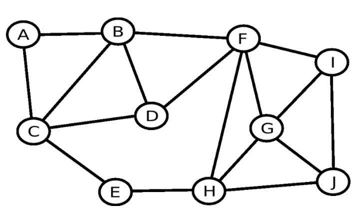
	9	0	4	1	5	0
	9	1	3	1	1	4
Core i	1	0	4	6	0	7
	2	1	0	0	0	0
Core j	0	0	0	1	0	0
	0	0	1	1	1	0

Matrix Multiplication

- Naive:
  $O(n^3)$ multiplications
  - Small rounding errors
- Better: Strassen
  $O(n^{2.807})$ multiplications
  - Re-use partial results
  - Can also be done in parallel
- Even better? Coppersmith-Winograd
  $O(n^{2.375477})$ multiplications
  - Asymptotically better
  - But not for practical matrix sizes

All-Pairs Shortest Path

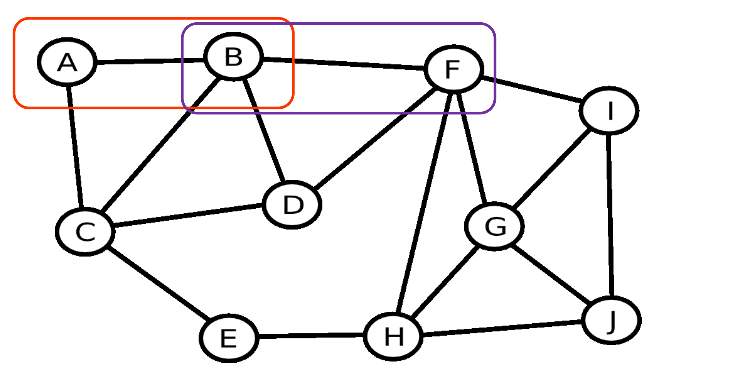
- Some problems can be represented nicely by matrices
- Let $G = (V, E)$ be a connected graph. The adjacency matrix M of G has a 1-entry on $M(u, v)$ if there is an edge between nodes u and v



	A	B	C	D	E	F	G	H	I	J
A	0	1	1	0	0	0	0	0	0	0
B	1	0	1	1	0	1	0	0	0	0
C	1	1	0	1	1	0	0	0	0	0
D	0	1	1	0	0	1	0	0	0	0
E	0	0	1	0	0	0	0	1	0	0
F	0	1	0	1	0	0	1	1	1	0
G	0	0	0	0	0	1	0	1	1	1
H	0	0	0	0	1	1	1	0	0	1
I	0	0	0	0	0	1	1	0	0	1
J	0	0	0	0	0	0	1	1	1	0

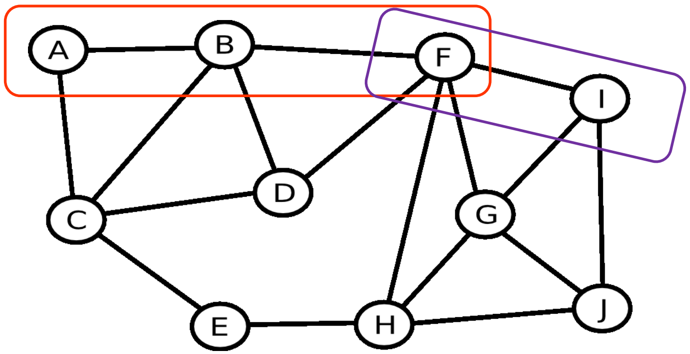
All-Pairs Shortest Path

- The adjacency matrix gives us all nodes at distance 1
- To get nodes at distance 2, multiply the adjacency matrix by itself
- $M^2(A, F) = M(A, A)M(A, F) + M(A, B)M(B, F) + \ldots + M(A, F)M(F, F) \geq 1$



Solving the All-Pairs Shortest Path Problem

- Similarly, get nodes at distance 3 by multiplying M^2 by M:
  $M^3(A, I) = M^2(A, A)M(A, I) + M^2(A, F)M(F, I) + \dots \geq 1$



All-Pairs Shortest Path

- After i multiplications, $M(u, v) \neq 0$ if there is a path of length at most $i + 1$ from u to v
- After $diameter(G) - 1$ multiplications, we have found all nodes
- The length of the shortest path between any two nodes u and v is the index of the step i for which, $M^{(i-1)}(u, v) = 0$ and $M^i(u, v) \geq 1$
  - Write distances to output matrix Q
- We can store the partial paths found in the intermediate steps
  - get the actual shortest paths in the end

Conclusion

- OpenMP
  - Widely used in scientific computing
  - CPUs execute ‘real’ threads
    - Don’t have to execute the same line of code everywhere
- GPUs have way more cores than CPUs
  - Enables more parallelism
  - Cores execute the **same** instruction per clock cycle
  - Efficient for matrix operations
  - Can be programmed using
    - OpenCL
    - CUDA
    - possibly OpenMP in the future

Outlook

- Faults
  - OpenMP, OpenCL, CUDA don’t care about faults
  - Hadoop/MapReduce: Store all intermediate steps, for fault-tolerance
  - Apache Spark: Recompute intermediate steps in case of (rare) faults
- Bottlenecks
  - Solution to problem designed around the shortcomings of the hardware
  - Why don’t we design the hardware around our problem?
    Remove bottlenecks, fine-tune relative speed of system components
  - «MinuteSort with Flat Datacenter Storage», MSR
    Disk reads can be a bottleneck as well → Design whole datacenter around it
    Overlap disk reads with asynchronous sorting-passes of already available data
    Unbeaten entry from 2012 for ‘Number of elements sorted in 60 seconds’
    www.sortbenchmark.org

That's all, folks!

Questions & Comments?

Roger Wattenhofer