Simplifying Parallel Programming

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The Problem
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The Reason

\[ E = C \times V^2 \times f \]
More Correctly

\[ E = C \times V (f)^2 \times f \]
Use of Transistors

- Increasing frequency is out
- Two uses
  - More complex architecture
    - Handle existing instructions faster
    - More specialized instructions
  - Horizontal growth
    - More execution cores; or
    - Only more execution contexts

Requires Parallelism!
Cost of Too Little Parallelism

- Idealized Amdahl's Law

\[ S = \frac{1}{(1-P) + \frac{P}{N}} \]

- Problems
  - \( P \) too small
  - \( N \) is steadily growing
- Formula is unrealistic though…
A More Realistic Formula

- Extended Amdahl's Law with Overhead

\[ S = \frac{1}{(1-P) (1+O_s) + \frac{P}{N} (1+O_p)} \]

- Parallelization is not free
  - Most of the time not even for serial code
  - The results are not *that* bad…
Even with Overhead P=0.6

- Even with 40% overhead not that much slower
- Speed-up from two threads on
  - Eleven threads for 10x slowdown
Programming Goals

\[ S = \frac{1}{(1-P)(1+O_s) + \frac{P}{N}(1+O_p)} \]

- Two goals: 1. ease parallel programming to increase \( P \)
  2. reduce \( O_s \) and \( O_p \)
Getting Parallelism

- Multi-process Pipeline
Problems with Pipelines

- Marshalling needed for transmission
- Protocol standardization required
- Limited buffer sizes
  - Lots of scheduling needed
- Program need to be designed for pipeline
  - Extending an existing program not easy
  - Major code restructuring needed
Problems with Pipelines

- Marshalling needed for transmission
- Protocol standardization required
- Limited buffer sizes
  - Lots of scheduling needed
- Program need to be designed for pipeline
  - Extending an existing program not easy
  - **Major code restructuring needed**
Simple Program Structure

Common Data 1

Common Data 2

Function 1

Function 2

Dataset 1

Dataset 2

Dataset 3
“Easy” Fix

Process

Common Data 1

Thread 1

Thread 2

Common Data 2

Dataset 1

Dataset 2

Dataset 3
“Easy” Fix

Process

- Common Data 1
- Common Data 2
- Thread 1
- Thread 2
- Dataset 1
- Dataset 2
- Dataset 3
It seems easy...

Mutexes are hard to use right!!!
Explicit Multi-Threaded

- Ill-conceived solution
  - Yes
    - Existing code can be reused, easier to set up
    - High-bandwidth inter-thread communication
    - On some OSes context switching faster
  - But:
    - Fragile programming model (one thread dies, the process dies)
    - Memory handling mistakes have global effects
    - Unix model initially not designed for multiple threads

**Hard to write correct code! High Cost!**
Measures

- Dataset 1
- Dataset 2
- Dataset 3
- Thread 1
- Thread 2
- Mutex
- Mutex
- Common Data 1
- Common Data 2
- Process

Measures:
- Reuse
- Bandwidth
- Context Cost
- Unix model
- Ease Program
- Fragile
- Overwrites
- Error Prone
Alternative 1: fork and Shared Memory

- All in POSIX:

```c
int fd = shm_open(name, O_RDWR|O_CREAT);
ftruncate(fd, size);
p = mmap(NULL, size, PROT_READ|PROT_WRITE,
        MAP_SHARED, fd, 0);
if (fork() == 0)
    ...
```
fork and Shared Memory

- State Data
- Process 1
- Dataset 1
- Mutex
- Dataset 2
- Mutex
- Dataset 3
- Reuse
- Fragile
- Bandwidth
- Overwrites
- Context Cost
- Unix model
- Ease Program
- Error Prone
Alternative 2: fork and Linux Pipes

- Linux extensions, not POSIX (yet 😊)
- Can be zero-copy
- Use if just transferring data without inspection
- splice: transfer from file descriptor to pipe
- tee: transfer between pipes and keep data usable
- vmsplice: transfer from memory to pipe
fork and Linux Pipes

State Data

Process 1

Dataset 1

State Data

Process 2

Dataset 3

Pipe

Reuse
Bandwidth
Context Cost
Ease Program

Fragile
Overwrites
Unix model
Error Prone

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Alternative 3: Thread Local Storage

- Use thread-local storage
  - Very much simplifies use of static variables
  - No more false sharing of cache lines

```c
__thread struct foo var;
```
Thread Local Storage

- Dataset 1
- Dataset 2
- Dataset 3

- Thread 1
- Thread 2

- Common Data 1
- Common Data 2

- Mutex

- Process

- Reuse
- Bandwidth
- Context Cost

- Fragile
- Overwrites
- Unix model
- Error Prone

- Ease Program
Alternative 4: OpenMP

- Language extension to C, C++, Fortran languages
- Implements many thread functions with very simple interface for
  - Thread creation (controlled)
  - Exclusion
  - Thread-local Data
OpenMP
Alternative 5: Transactional Memory

- Extensions to C and C++ languages
- Can help to avoid using mutexes
  - Just source code annotations
  - No more deadlocks!!
  - Fine-grained locking without the problems
- Slow as pure software solutions
  - Hardware support on the horizon
Transaction System

Portfolio Data

- Person 1
- Person 2
- Person N

Bank 1
Bank 2
Bank N

Deduct Shares from Person 1
Add Shares to Person 2
Subtract from Person 2 Account
Add to Person 1 Account
Trying to Parallelize

Portfolio Data

Person 1

Person 2

Person N

Lock Domain

Bank 1

Bank 2

Bank N
Not What We Want

![Graph showing comparison between Single Core i7 and Opteron NUMA in terms of runtime vs. threads. The Single Core i7 has a sharp drop in runtime with an increase in threads, while the Opteron NUMA shows a more linear increase.]
Trying to Parallelize

Portfolio Data

Person 1

Person 2

Person N

Lock Domain

Bank 1

Bank 2

Bank N
Somewhat Better But…

![Graphs showing runtime with varying number of threads for Single Core i7 and Opteron NUMA systems. The graphs illustrate the relationship between threads and runtime for both architectures.]
Transactional Memory

![Diagram showing the relationship between threads, mutex, and datasets in a transactional memory system.]

- **Thread 1**
- **Thread 2**
- **Mutex**
- **Common Data 1**
- **Common Data 2**
- **Dataset 1**
- **Dataset 2**
- **Dataset 3**

**Issues**:
- **Reuse**
- **Bandwidth**
- **Context Cost**
- **Unix model**
- **Error Prone**
- **Fragile**
- **Overwrites**

**Process**
Conclusion

- Abilities to exploit hardware are there
  - Explicit threading only for experts
- But there is a lot of help
  - Use processes, not threads; or
  - If threads are used combine
    - Thread-local storage
    - Implicit thread creation
      - OpenMP
      - Futures
    - Transactional memory
Questions?
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