Parallelization Primer

by

Christian Bienia

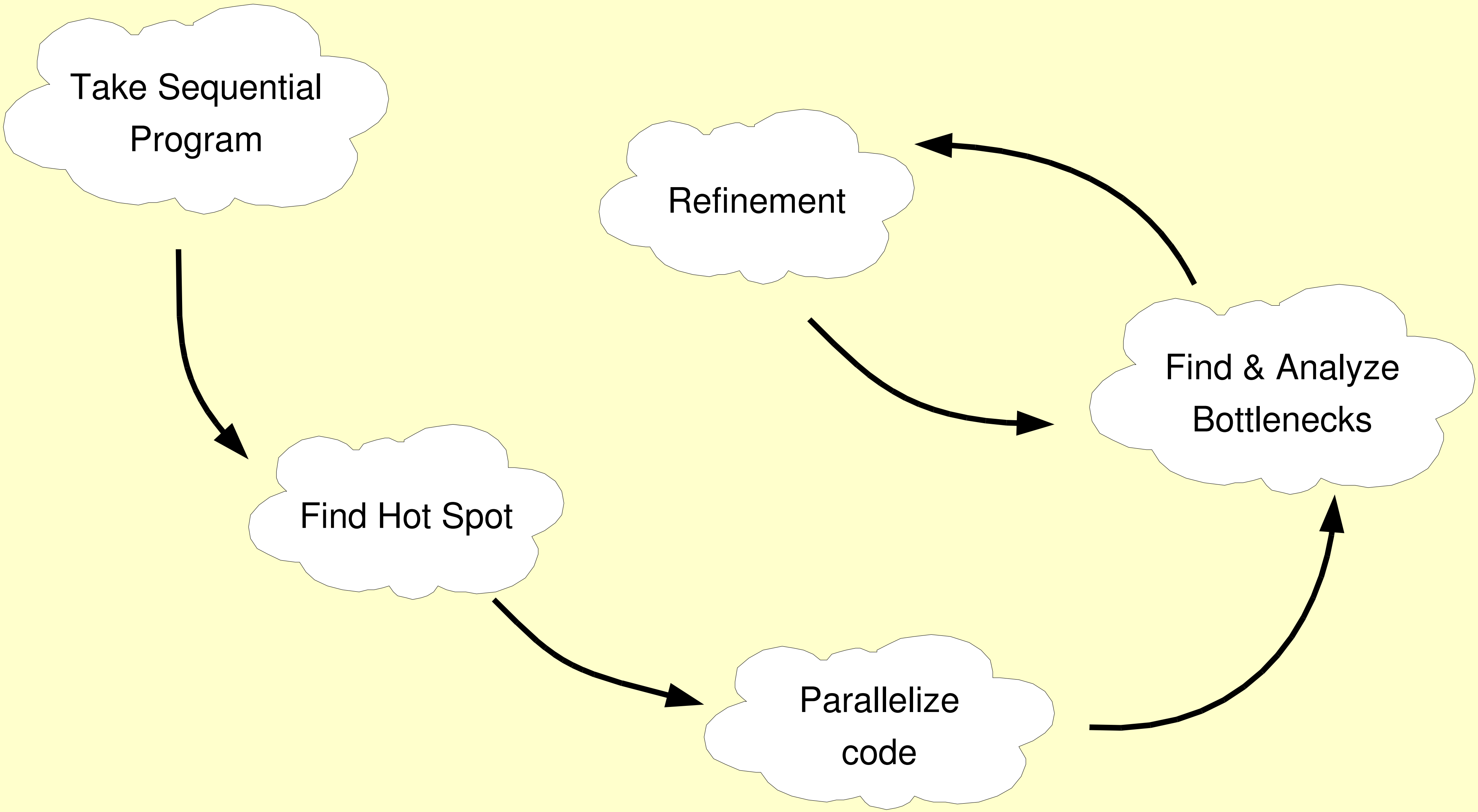
March 05, 2007

What is Parallelization?

Answer: The creation of a new algorithm!

- Trivial case: Run sequential algorithm on multiple CPUs, throw locks around shared data
- Common case: Rewrite & extend parts of sequential algorithm
- Hard case: Rewrite program from scratch

So how does it work?



Metrics

Speedup $S_p = T_1 / T_p$

Ideal Speedup $S_p = p$

Parallel Efficiency $E_p = S_p / p$

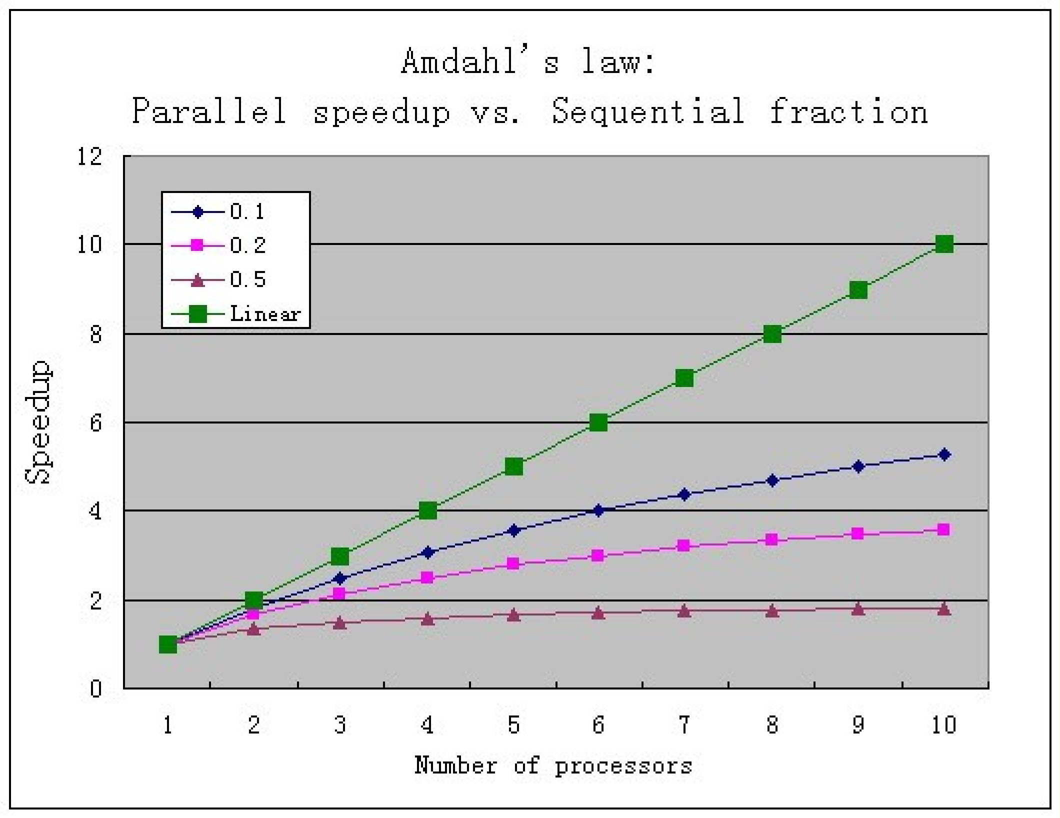
Preparation

Choosing a Sequential Program

- Not all programs can be parallelized
  - Example: Some cryptographic programs
- Must be CPU bound
- Well-written programs make your life easier
- You already made this step

Finding the Hot Spot: Profiling

- Use a profiler like `gprof` to find the hot spot
- Remember Amdahl's Law:



You need at least 99.9% of the program runtime!

Preparing your program

Compile & link <u>all files</u> of your program with profiling support:

```
gcc -O3 -g -pg prog.c -o prog
```

WARNING: `gprof` doesn't work correctly with multi-threaded programs. Details & Workaround:

http://sam.zoy.org/writings/programming/gprof.html

WARNING 2: Even then, improper parallelization can give you distorted timing results!

Using `gprof`

- Run your program with typical input:

```
./prog 40
Result: N! = 18376134811363311616
```

- Run `gprof` on program & profile data file (`gmon.out`):

```
gprof prog
...
```

Profiling Example: N!

```
#include <stdio.h>
#include <stdlib.h>
#include <inttypes.h>

/* Compute n! */
uint64_t factorial(uint64_t n) {
  if(n <= 1) return 1;
  return n * factorial(n - 1);
}

int main(int argc, char **argv) {
  int i, n;
  uint64_t fac;

  n = atoi(argv[1]);
  for(i=0; i<1000000; i++) fac = factorial(n);
  printf("Result: N! = %"PRIu64"\n", fac);
  return 0;
}
```

Output of `gprof` (Excerpt)

```
        Call graph (explanation follows)


granularity: each sample hit covers 2 byte(s) for 5.20% of 0.19
seconds

index % time    self  children    called     name
                                                 <spontaneous>
[1]     73.7    0.01    0.13                    main [1]
                0.13    0.00 1000000/1000000     factorial [2]
-----------------------------------------------
                             38000000             factorial [2]
                0.13    0.00 1000000/1000000     main [1]
[2]     68.4    0.13    0.00 1000000+38000000 factorial [2]
                             38000000             factorial [2]
-----------------------------------------------
                                                 <spontaneous>
[3]     26.3    0.05    0.00                    frame_dummy [3]
-----------------------------------------------
```

Limitations of `gprof`

- Profiling multi-threaded programs can give you misleading results
- Results depend on chosen input
- Need to compile all code with profiling support to get accurate results – What about shared libraries?
- Profiling information limited by sampling granularity

Parallelization

Why is Parallelization hard?

- Magnitude: Timing-related issues in addition to sequential logic errors
- Determinism: Parallel programs are non-deterministic
- Expression: Data synchronization separate from data
- Biology: Humans can't think concurrently

What to do about it?

- You <u>must</u> work systematically and with methodology
- You <u>must</u> get it right the first time (or at least as much as possible)
- Hacking won't work
- Search for previous work on parallelization of your algorithms

Synchronization

Accesses to shared data which is updated during parallel phase must be synchronized.

- Best approach is to eliminate need for synchronization!
- Synchronization is expensive: Try to defer and aggregate updates

Shared Data

- Possible locations of shared data:
  - Global variables
  - Static variables in functions
  - Heap allocated data (shared pointers)
- Use good engineering to add locks:

```
struct {
    int count;
    void *list;
    pthread_mutex_t list_mutex;
} shared_list;
```

Pthreads - You already know...

- Mutexes
- Condition variables
- MESA-style monitors:

```
pthread_mutex_lock(&mutex);
while (!cond) {
    pthread_cond_wait(&condvar, &mutex);
}
do_work();
pthread_cond_signal(&other_cond);
pthread_mutex_unlock(&mutex);
```

Pthreads – But there's more!

- Barriers: Wait for specified number of threads
- Rwlocks: Concurrent reads & sequential writes
- Spinlocks: Don't block, spin (for short waits)
- Trylocks: Don't block, return result of lock operation immediately
- Timed locks: Try to acquire lock, but only wait up to specified amount of time

Deadlocks

Four necessary conditions for deadlocks:

- Mutual Exclusion
- Hold and Wait
- No Preemption
- Circular Wait

Deadlock Avoidance

- You need a locking protocol
- Define a *partial order* on locks:

$$lock_1 <_P lock_2 <_P lock_3 <_P \ldots <_P lock_N$$

- Acquire locks only in this order (no circular wait)
- Deadlocks are a symptom of poorly designed software

Race Conditions

- You forgot to synchronize accesses to shared data
- Non-deterministic, can be very hard to find
- Tool for automatic detection: `helgrind` (part of Valgrind tool suite, see http://www.valgrind.org/)

`helgrind` Overview

- Uses Eraser algorithm: Stefan Savage et al. “Eraser: A Dynamic Data Race Detector for Multithreaded Programs”
- Usage:

```
valgrind --tool=helgrind ./race
```

- Unavailable in Valgrind release 2.4 and later, use an older version

Data Race Example

```
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>

int counter = 0;

void *threadx(void *arg) {
  int i;
  for(i=0; i<10; i++) { counter++; printf("x"); sleep(1); }
}

void *thready(void *arg) {
  int i;
  for(i=0; i<10; i++) { counter++; printf("o"); sleep(1); }
}

void main() {
  pthread_t tx, ty;
  pthread_create(&tx, NULL, &threadx, NULL);
  pthread_create(&ty, NULL, &thready, NULL);
  pthread_join(tx, NULL);
  pthread_join(ty, NULL);
  printf("\nCounter: %i\n", counter);
}
```

Output of `helgrind` (Excerpt)

```
==25878== Helgrind, a data race detector for x86-linux.
==25878== Copyright (C) 2002-2004, and GNU GPL'd, by Nicholas Nethercote et
al.
==25878== Using valgrind-2.2.0, a program supervision framework for x86-
linux.
==25878== Copyright (C) 2000-2004, and GNU GPL'd, by Julian Seward et al.
==25878== For more details, rerun with: -v
==25878==
==25878== Thread 3:
==25878== Possible data race writing variable at 0x80497C8
==25878==    at 0x8048500: thready (race.c:14)
==25878==    by 0x1D4AFCDA: thread_wrapper (vg_libpthread.c:867)
==25878==    by 0xB000F714: do__quit (vg_scheduler.c:1872)
==25878==  Address 0x80497C8 is in BSS section of
/n/fs/grad/cbienia/course/race/race
==25878==  Previous state: shared RO, no locks
...
xoxoxoxoxoxoxoxoxoxo
Counter: 20
...
==25878== ERROR SUMMARY: 11 errors from 11 contexts (suppressed: 5 from 2)
==25878== 16 possible data races found; 0 lock order problems
```

Limitations of `helgrind`

- False negatives (not all data races will be detected)
- False positives (lots of output)
- Only supports x86 processors

Refinement

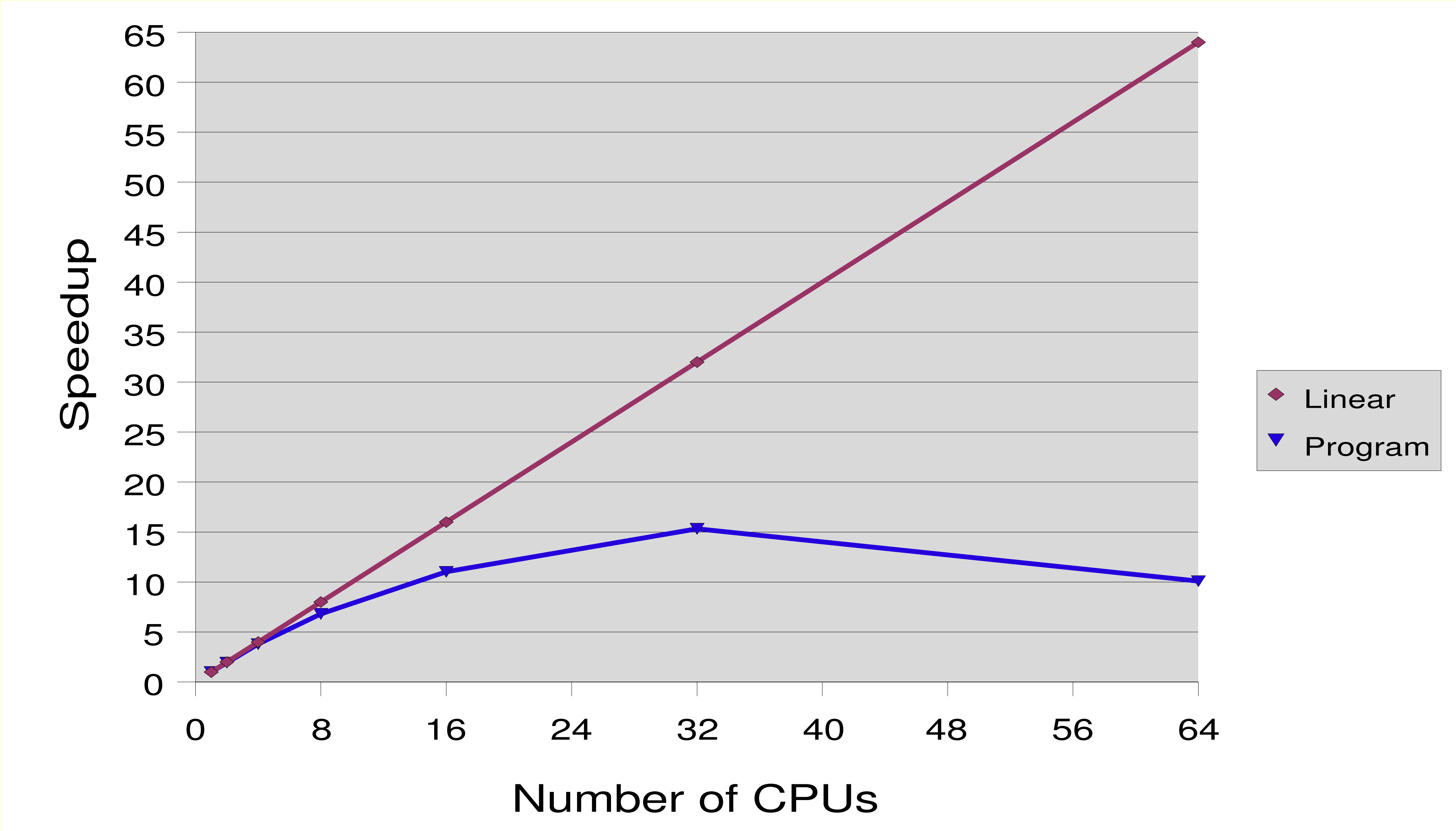
Refining Synchronization: `pthreadw`

- `pthreadw` is a thread library wrapper
- Collects synchronization statistics during runtime
- No recompilation required, but recommended
- Usage:

```
pthreadw ./prog
```

- Author of `pthreadw` is talking to you right now

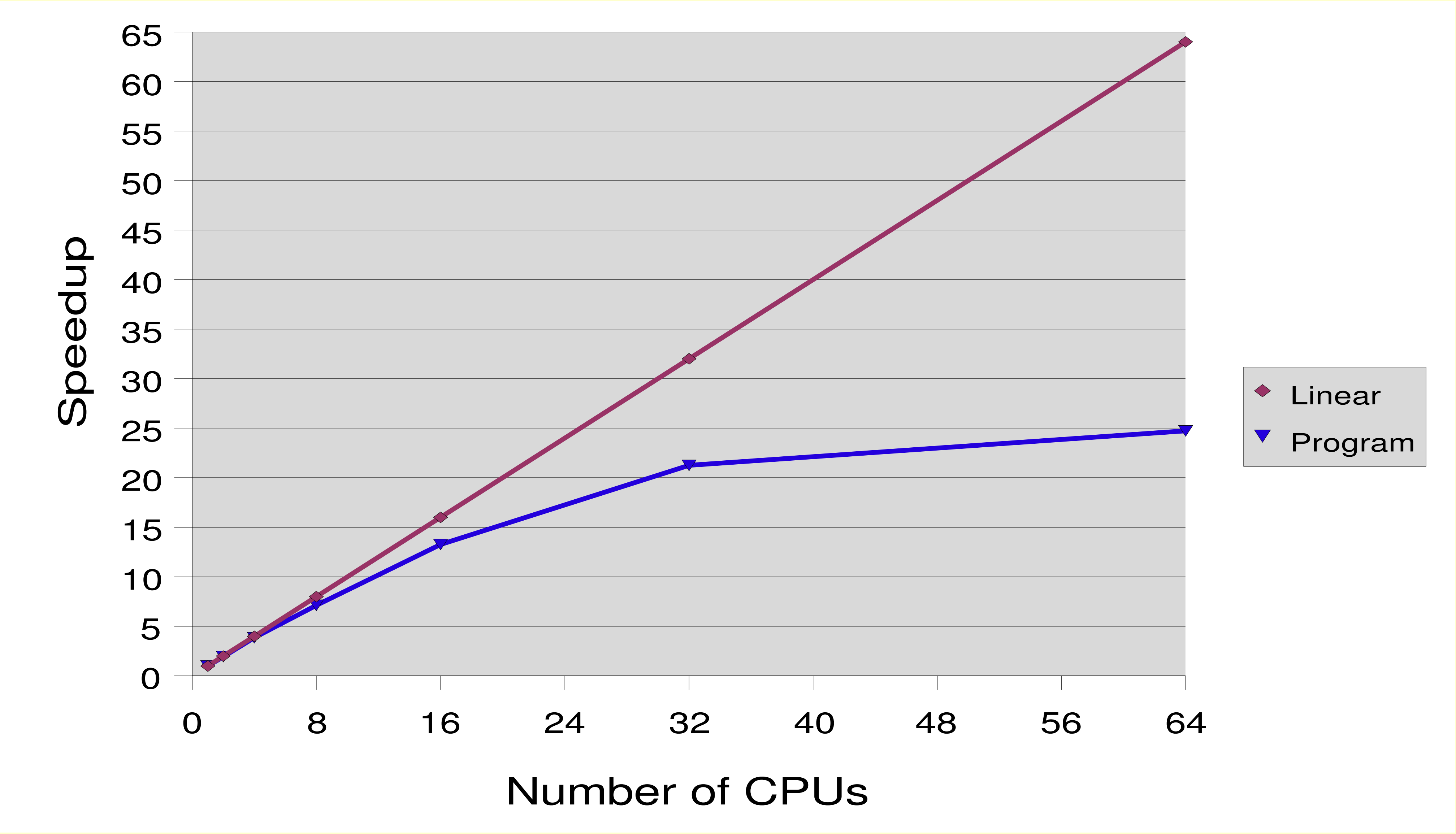
Hot Lock Example



Output of `pthreadw` (Excerpt)

```
[pthreadw] Mutex functions:
[pthreadw]   g_mutex_lock:
[pthreadw]     - number of calls                         23317786
[pthreadw]     - blocking rate                           15.54%
[pthreadw]     - total elapsed time                      3289577074436 ns
[pthreadw]     - share of total CPU time                 66.35%
[pthreadw]     - time per call (mean)                    141075.9 ns
[pthreadw]     - share of thread lifetime (mean)         66.36%
...
[pthreadw] Mutex variables:
[pthreadw]   Rank     Name / Addr              Time [ns]         Uses   Contention
[pthreadw]     1. 0x6000000000021350  3104207952264 (62.6%)   800764      29.3%
[pthreadw]      Uses: -  0.0% as N/A in im_init() (im_init.c:133)
[pthreadw]            -  0.0% as im->sslock in im__call_stop() (region.c:139)
[pthreadw]            -  0.0% as im->sslock in im__call_stop() (region.c:141)
[pthreadw]            - 20.0% as im->sslock in im_buffer_unref() (buffer.c:65)
[pthreadw]            - 20.0% as im->sslock in im_buffer_unref() (buffer.c:111)
...
[pthreadw]            - 20.0% as im->sslock in im_buffer_ref() (buffer.c:214)
[pthreadw]            - 20.0% as im->sslock in im_buffer_ref() (buffer.c:225)
[pthreadw]            -  0.0% as im->sslock in im__call_start() (region.c:112)
[pthreadw]            -  0.0% as im->sslock in im__call_start() (region.c:114)
[pthreadw]            -  9.9% as im->sslock in im_buffer_done() (buffer.c:122)
[pthreadw]            -  9.9% as im->sslock in im_buffer_done() (buffer.c:128)
```

Result of Hot Lock Elimination



Limitations of `pthreadw`

- Only detects issues related to synchronization
- Slows down program
- Might affect thread schedule
- Does not detect non-standard forms of synchronization

Other Reasons for Bad Scalability

- Incomplete list, in no particular order:
  - Program becomes I/O bound
  - Program becomes memory bound
  - Thrashing
  - More spinning
  - Increasing number of cache misses
  - ...

Instrumentation

- Instrument your source code to find bottlenecks
- You need a timer with very high precision.
- Recommendation: `clock_gettime()`
- To use `clock_gettime()`, you have to `#include <time.h>` and link with librt (`-lrt`)
- Store counter values in `uint64_t` from `inttypes.h`

Thank you!