

Lecture 17:
Performance Monitoring Tools

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2019

Scenario

- **Student walks into office hours and says, “My code is slow / uses lots of memory / is SIGKILLED. I implemented X, Y, and Z. Are those good? What should I do next?”**
- **It depends.**

What is my program doing?

- **Measurements are more valuable than insights**
 - **Insights are best formed from measurements!**

- **We're Computer Scientists**
 - **We can write programs to analyze programs**

Note about Examples

- **The example programs in today's lecture are from Spring 2016 Assignment 3**
 - **OpenMP-based graph processing workload (paraGraph)**
 - **Millions to tens of millions of nodes**
 - **Code written for the GHC machines and Xeon Phi**

My program is slow today.

- What else is running?
 - Try "top"

```
top - 14:43:26 up 25 days, 3:46, 50 users, load average: 0.04, 0.05, 0.01
Tasks: 1326 total, 1 running, 1316 sleeping, 2 stopped, 4 zombie
Cpu(s): 0.0%us, 0.1%sy, 0.0%ni, 99.9%id, 0.0%wa, 0.0%hi, 0.0%si, 0.0%st
Mem: 16220076k total, 7646188k used, 8573888k free, 246280k buffers
Swap: 4194296k total, 3560k used, 4190736k free, 5219176k cached
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
2801	nobody	20	0	481m	3860	1192	S	1.0	0.0	63:45.33	gmetad
3306	root	20	0	258m	11m	2128	S	0.7	0.1	161:54.86	lsi_mrdsnmpagen
4920	nobody	20	0	297m	18m	3380	S	0.7	0.1	181:11.80	gmond
49781	-----	20	0	106m	2144	1456	S	0.3	0.0	0:00.10	bash
58119	bpr	20	0	15976	2220	936	R	0.3	0.0	0:00.30	top
106182	-----	20	0	24584	2184	1136	S	0.3	0.0	2:27.99	tmux
134225	-----	20	0	143m	1732	608	S	0.3	0.0	0:02.92	intelremotemond
...											

What else can top tell us?

- CPU / Memory usage of our program

– ./paraGraph kbfs com-orkut_117m.graph -t 8 -r

```
top - 15:54:27 up 3 days, 23:58, 6 users, load average: 3.43, 1.15, 0.43
Tasks: 286 total, 2 running, 284 sleeping, 0 stopped, 0 zombie
%Cpu(s): 99.8 us, 0.2 sy, 0.0 ni, 0.0 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
KiB Mem: 32844548 total, 31305468 used, 1539080 free, 435012 buffers
KiB Swap: 7999484 total, 13176 used, 7986308 free. 27364456 cached Mem
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
23457	bpr	20	0	1559584	979704	3420	R	796.4	3.0	0:27.91	paraGraph
1071	root	20	0	75892	6560	5564	S	2.0	0.0	19:58.05	cups-brows+
21506	root	20	0	87680	17300	5460	S	0.7	0.1	1:08.43	cupsd
23408	bpr	20	0	24956	3196	2588	R	0.3	0.0	0:00.18	top
1	root	20	0	36100	4204	2632	S	0.0	0.0	0:01.02	init

Do I have to use top?

- **No. Time was part of the assignment 3 qsub jobs.**

```
$ tail -n 1 bpr_grade_performance.job  
time ./grade_performance.py ./$exe
```

- **time is often a shell command, there is also the time binary**

- ```
/usr/bin/time ./paraGraph kbfs com-orkut_117m.graph -t 8 -r
...
33.16user 0.10system 0:05.54elapsed 600%CPU (0avgtext+0avgdata
979708maxresident)k 0inputs+0outputs
(0major+5624minor)pagefaults 0swaps
```

# But why is it slow?

- **Where is the time spent?**
  - **Put timing statements around probable issues**
  - **Print results**
  
- **OR**
  - **Use a tool to insert timing statements**



# Program Instrumentation

- **When to inject the instrumentation?**
  - **When the program is compiled.**
  - **When the program is run.**

# Instrumentation Tool Families

- **Program Optimization**
  - **Gprof**
  - **Perf**
  - **VTune**
- Program Debugging
  - Valgrind
  - Sanitizers
- Advanced Analysis
  - Pin
  - Contech

# Amdahl's Law Revisited

- $1 - s$  – a component of the program
- $p$  – speedup of that component
- The more time something takes
  - The more speedup small improvements make
- Concentrate program optimization on:
  - Hot code
  - Common cases

$$\text{speedup} \leq \frac{1}{s + \frac{1-s}{p}}$$

# GProf

- Enabled with “-pg” compiler flag
- Places a call into every function
  - Calls record the call graph
  - Calls record time elapsed
- Run the program.
- Run `gprof <prog name>`

# GProf cont

- **Output shows both the total time in each function**
  - **And cumulative time in calling trees**
- **Can be useful with large call graphs**
- `$/paraGraph pagerank -t 8 -r soc-pokec_30m.graph`
- `$gprof`

| %<br>time | cumulative<br>seconds | self<br>seconds | calls   | self<br>ms/call | total<br>ms/call | name                         |
|-----------|-----------------------|-----------------|---------|-----------------|------------------|------------------------------|
| 69.35     | 0.43                  | 0.43            | 1       | 430.00          | 430.00           | build_incoming_edges(graph*) |
| 30.65     | 0.62                  | 0.19            | 18      | 10.56           | 10.56            | pagerank(graph*, ...)        |
| 0.00      | 0.62                  | 0.00            | 1632803 | 0.00            | 0.00             | addVertex(VertexSet*, int)   |
| 0.00      | 0.62                  | 0.00            | 7       | 0.00            | 0.00             | newVertexSet(T, int, int)    |
| 0.00      | 0.62                  | 0.00            | 7       | 0.00            | 0.00             | freeVertexSet(VertexSet*)    |

# Perf

- **Modern architectures expose performance counters**
  - **Cache misses, branch mispredicts, IPC, etc**
- **Perf tool provides easy access to these counters**
  - **perf list – list counters available on the system**
  - **perf stat – count the total events**
  - **perf record – profile using one event**
  - **perf report – Browse results of perf record**
- **Perf is present on GHC machines tested**

# Perf stat

- **Can be run with specific events or a general suite**
- **perf stat [-e ...] app**
  - **Many counters come in pairs, each needs a separate -e**
    - **cycles, instructions**
    - **branches, branch-misses**
    - **cache-references, cache-misses**
    - **stalled-cycles-frontend**
    - **stalled-cycles-backend**
  - **Processors can only enable ~4 counters, else it must multiplex**

# Perf stat (default) output

```
./paraGraph -t 8 -r pagerank /afs/cs/academic/class/15418-s16/public/asst3_graphs/soc-
pokec_30m.graph':
```

```
2366.633970 task-clock (msec) # 1.758 CPUs utilized
 109 context-switches # 0.046 K/sec
 9 cpu-migrations # 0.004 K/sec
 6,168 page-faults # 0.003 M/sec
7,513,900,068 cycles # 3.175 GHz (83.23%)
6,327,732,886 stalled-cycles-frontend # 84.21% frontend cycles idle (83.42%)
4,019,403,839 stalled-cycles-backend # 53.49% backend cycles idle (66.86%)
3,222,030,372 instructions # 0.43 insns per cycle
 # 1.96 stalled cycles per insn (83.43%)
457,170,532 branches # 193.173 M/sec (83.30%)
12,354,902 branch-misses # 2.70% of all branches (83.24%)
```

So what is the bottleneck?



# More perf stat

- **Maybe memory is a bottleneck.**

```
201,493,787 cache-references
 49,347,882 cache-misses # 24.491 % of all cache refs
```

- **24% misses, that's not good.**
- **But what should we do?**

# Perf record

- **Pick an event (or use the default cycles)**
- **When the event's counter overflows**
  - **The processor sends an interrupt**
  - **The kernel records where (PC value) of the program**
- **NOTE: counters update in funny, microarchitectural ways so intuition may be required**

**“Because of latency in the microarchitecture between the generation of events and the generation of interrupts on overflow, it is sometimes difficult to generate an interrupt close to an event that caused it.”**

# Perf cache misses

- Are cache misses the problem?
  - Sort of.

Samples: 11K of event 'cache-misses', Event count (approx.):  
181771931

| Overhead | Command   | Shared Object | Symbol                      |
|----------|-----------|---------------|-----------------------------|
| 47.18%   | paraGraph | paraGraph     | [.] edgeMapS<State<float> > |
| 46.84%   | paraGraph | paraGraph     | [.] build_incoming_edges    |
| 2.70%    | paraGraph | [unknown]     | [k] 0xffffffff813b2537      |
| 1.37%    | paraGraph | [unknown]     | [k] 0xffffffff813b2915      |

# Perf report cycles

- perf report shows analysis from record
  - Commandline interactive interface

Samples: 13K of event 'cycles', Event count (approx.): 11108635969

| Overhead | Command   | Shared Object     | Symbol                       |
|----------|-----------|-------------------|------------------------------|
| 65.93%   | paraGraph | paraGraph         | [.] edgeMapS<State<float> >  |
| 27.66%   | paraGraph | paraGraph         | [.] build_incoming_edges     |
| 1.85%    | paraGraph | paraGraph         | [.] vertexMap<Local<float> > |
| 1.02%    | paraGraph | [kernel.kallsyms] | [k] clear_page_c             |
| 0.88%    | paraGraph | paraGraph         | [.] addVertex                |
| 0.60%    | paraGraph | [kernel.kallsyms] | [k] copy_user_generic_string |

- Over 25% of program time is in creating the graph
  - This also skews the perf stats

# Deep dive

- Selecting a function will display its assembly with function-local %

```
| bool update(Vertex s, Vertex d)
| {
| float add = pcurr[s] / outgoing_size(graph, s);
2.97 | divss %xmm1,%xmm0
5.22 | jmp 162
| nop
|160: mov %eax,%edx
| #pragma omp atomic
| pnext[d] += add;
0.16 |162: mov %edx,0x18(%rsp)
1.28 | mov %edx,%eax
0.01 | movss 0x18(%rsp),%xmm2
2.71 | addss %xmm0,%xmm2
4.63 | movss %xmm2,0x18(%rsp)
1.16 | mov 0x18(%rsp),%r15d
3.99 | lock cmpxchg %r15d,(%rcx)
25.22 | cmp %eax,%edx
| jne 160
```

1. OMP atomic -> lock cmpxchg
2. This instruction is 25%\*65% of execution time

# Deep dive 2

- **kBFS is really, really slow. Why?**

Samples: 48K of event 'cycles', Event count (approx.):  
39218498652

| Overhead | Command   | Shared Object | Symbol                     |
|----------|-----------|---------------|----------------------------|
| 63.78%   | paraGraph | paraGraph     | [.] edgeMapS<RadiiUpdate>  |
| 19.33%   | paraGraph | paraGraph     | [.] edgeMap<RadiiUpdate>   |
| 8.21%    | paraGraph | paraGraph     | [.] build_incoming_edges   |
| 3.88%    | paraGraph | paraGraph     | [.] vertexMap<VisitedCopy> |

- **That's almost all my code. :(**

# Disassemble it!

## ■ What is taking all of kbfs's time?

```
bool update(Vertex src, Vertex dst) {
 | bool changed = false;
 | for (int j = 0; j < NUMWORDS; j++) {
 | if (visited[dst][j] != visited[src][j]) {
0.11 | mov 0x0(%r13),%rax
0.21 | mov (%rax,%rdi,1),%rbp
0.20 | mov (%rax,%rcx,8),%rax
14.88 | mov 0x0(%rbp),%ebp
1.15 | mov (%rax),%eax
68.27 | cmp %eax,%ebp
0.02 | je 108
 | // word-wide or
 | __sync_fetch_and_or(&(nextVisited[dst][j]), visited[dst]
1.54 | mov 0x8(%r13),%rcx
0.34 | or %eax,%ebp
0.02 | mov (%rcx,%rdi,1),%rcx
0.31 | lock or %ebp,(%rcx)
 | int oldRadius = radii[dst];
 | if (radii[dst] != iter) {
6.45 | mov 0x18(%r13),%ebp
```

# VTune

- **Part of Intel's Parallel Studio XE**
  - **Requires (free student) license from Intel**
- **Similar to perf**
  - **Also includes analysis across related counters**



# **VTune Memory Bound**

- **That Spring, I asked many students in office hours:**
  - **“Do you think the graph code is memory bound?”**
  
- **Let’s find out!**
  - **Create a project (select program + arguments to analyze)**
  - **Create an analysis**
    - **Microarchitecture -> Memory Access Analysis**
  - **Start!**

# Memory Access Analysis Results

Am Memory Access Memory Usage viewpoint (change) ? Intel VTune Amplifier XE 2016

< Analysis Target Analysis Type Collection Log Summary Bottom-up Platform >

## Elapsed Time <sup>?</sup>: 0.713s

CPU Time <sup>?</sup>: 2.484s

Memory Bound <sup>?</sup>: 50.5%

The metric value is high. This can indicate that the significant fraction of execution pipeline slots could be stalled due to demand memory load and stores. Use VTune Amplifier XE Memory Access analysis to have the metric breakdown by memory hierarchy, memory bandwidth information, correlation by memory objects.

L1 Bound <sup>?</sup>: 0.027

L2 Bound <sup>?</sup>: 0.020

L3 Bound <sup>?</sup>: 0.127

This metric shows how often CPU was stalled on L3 cache, or contended with a sibling Core. Avoiding cache misses (L2 misses/L3 hits) improves the latency and increases performance.

DRAM Bound <sup>?</sup>: 0.320

This metric shows how often CPU was stalled on the main memory (DRAM). Caching typically improves the latency and increases performance.

Other: 1.2%

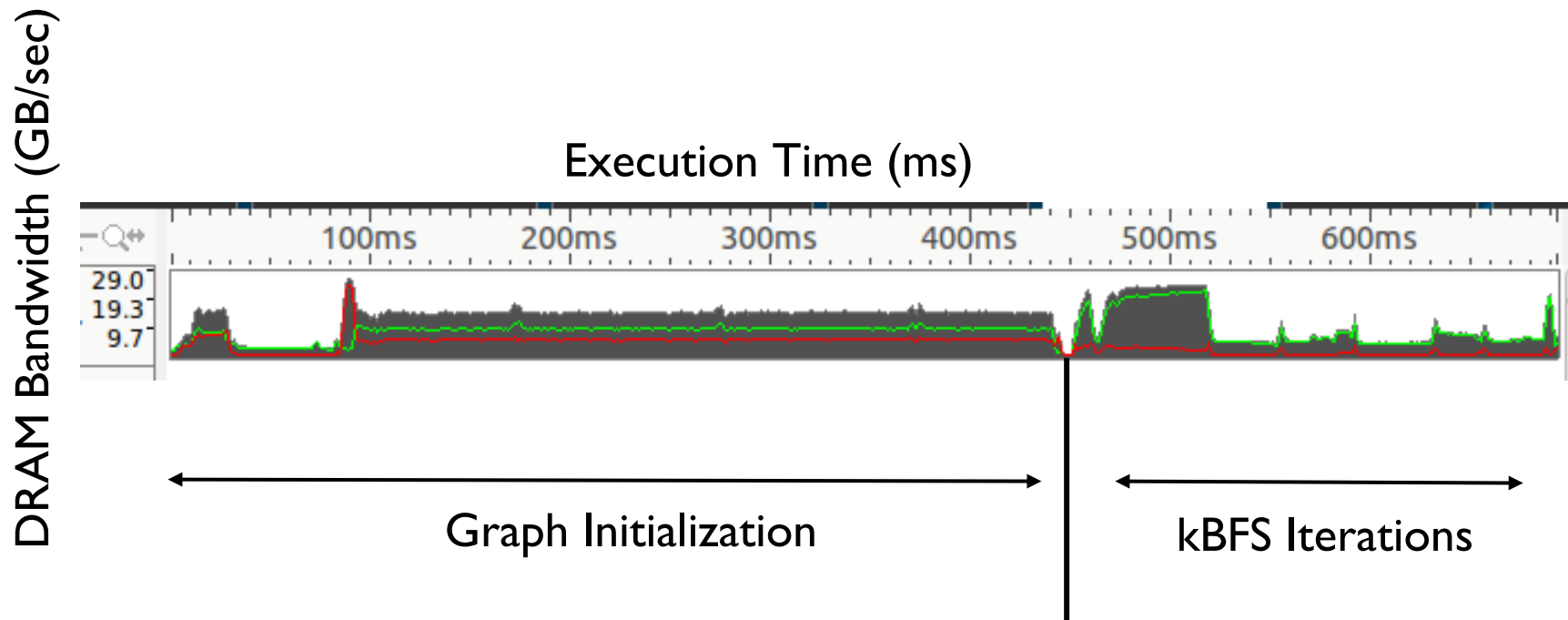
Average Latency (cycles) <sup>?</sup>: 22

Total Thread Count: 8

Paused Time <sup>?</sup>: 0s

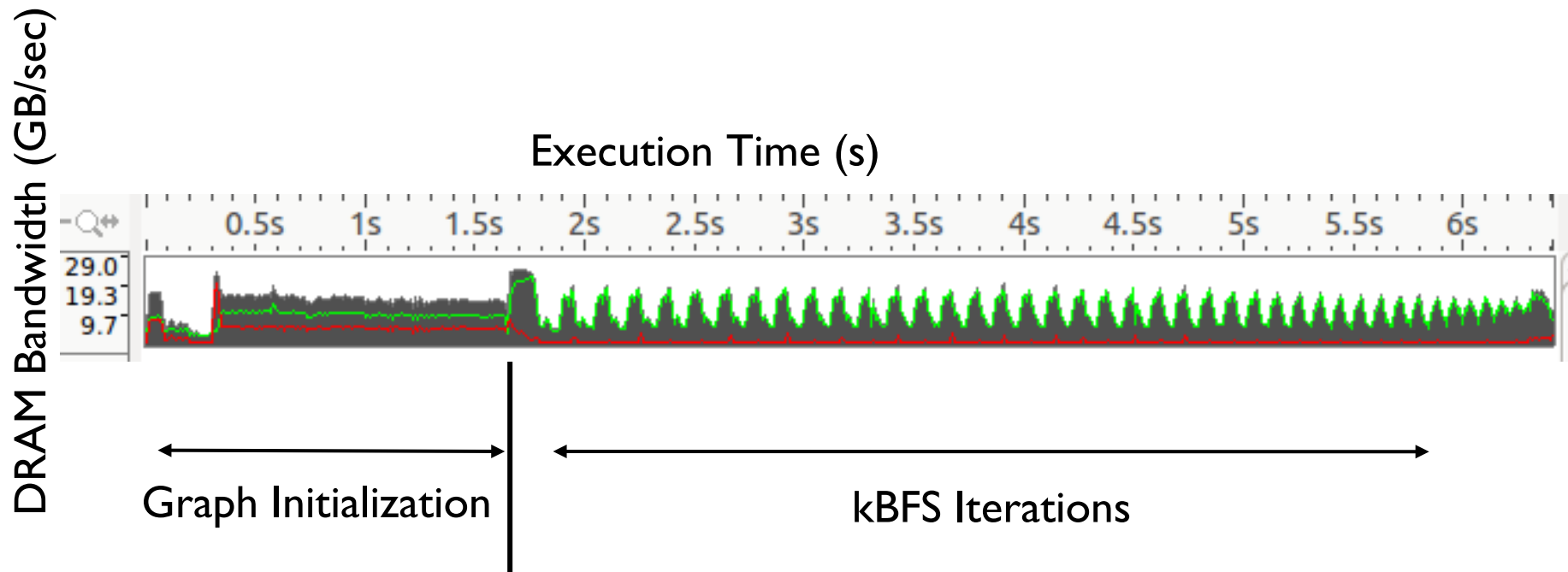
# Further Analysis

- Input: soc-pokec...



# Further Analysis

- Input: com-orkut



# Instrumentation Tool Families

- Program Optimization
  - Gprof
  - Perf
  - VTune
- **Program Debugging**
  - **Valgrind**
  - **Sanitizers**
- Advanced Analysis
  - Pin
  - Contech

# Valgrind

- **Heavy-weight binary instrumentation**
  - **Designed to shadow all program values: registers and memory**
  - **Shadowing requires serializing threads**
  - **4x overhead minimum**
  
- **Comes with several useful tools**
  - **Usually used for memcheck**

# Valgrind memcheck

- **Validates memory operations in a program**
  - **Each allocation is freed only once**
  - **Each access is to a currently allocated space**
  - **All reads are to locations already written**
  - **10 – 20x overhead**

- **valgrind --tool=memcheck <prog ...>**

```
...
==29991== HEAP SUMMARY:
==29991== in use at exit: 2,694,466,576 bytes in 2,596 blocks
==29991== total heap usage: 16,106 allocs, 13,510 frees, 3,001,172,305 bytes allocated
==29991==
==29991== LEAK SUMMARY:
==29991== definitely lost: 112 bytes in 1 blocks
==29991== indirectly lost: 0 bytes in 0 blocks
==29991== possibly lost: 7,340,200 bytes in 7 blocks
==29991== still reachable: 2,687,126,264 bytes in 2,588 blocks
==29991== suppressed: 0 bytes in 0 blocks
```

# Address Sanitizer

- **Compilation-based approach to detect memory issues**
  - GCC and LLVM support
  - ~2x overhead
  
- **Add “-fsanitize=address”, make clean ...**

```
==1902== ERROR: AddressSanitizer: heap-buffer-overflow on address 0x7f683e4c008c
at pc 0x41cb77 bp 0x7f683bc14a20 sp 0x7f683bc14a18
READ of size 4 at 0x7f683e4c008c thread T6
#0 0x41cb76 (paraGraph+0x41cb76)
#1 0x7f6852efdf62 (/usr0/local/lib/libiomp5.so+0x89f62)
#2 0x7f6852ea7ae3 (/usr0/local/lib/libiomp5.so+0x33ae3)
#3 0x7f6852ea620a (/usr0/local/lib/libiomp5.so+0x3220a)
#4 0x7f6852ecab80 (/usr0/local/lib/libiomp5.so+0x56b80)
#5 0x7f684fdb7b97 (/usr/lib/x86_64-linux-gnu/libasan.so.0.0.0+0x18b97)
#6 0x7f684efa4181 (/lib/x86_64-linux-gnu/libpthread-2.19.so+0x8181)
#7 0x7f684f2b447c (/lib/x86_64-linux-gnu/libc-2.19.so+0xfa47c)
...
```



# Instrumentation Tool Families

- Program Optimization
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  - Sanitizers
- **Advanced Analysis**
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  - **Contech**

# Pin

- **CompArch research project, now Intel tool**
- **Binary instrumentation tool framework**
  - **“Low” overhead**
  - **Provides many sample tools**
- **Given its architecture roots, it is best suited to specific architectural questions about a program**
  - **What is the instruction mix?**
  - **What memory addresses does it access?**

# Pin cont.

- **Pin acts as a virtual machine**
  - **It reassembles the instructions with appropriate instrumentation**
- **Each “pintool” requests specific instrumentation**
  - **On basic block entry, record the static instruction count**
  - **On every memory operation, record the address**
  - ...

# **(Pin) Instrumentation Granularity**

- **Instruction**
- **Basic Block**
  - **A sequence of instructions**
  - **Single entry, single exit**
  - **Terminated with one control flow instruction**
- **Trace**
  - **A sequence of executed basic blocks**
  - **May span multiple functions**

# Pintool Example Instruction Count

- For every basic block in an identified trace
  - Insert somewhere in the block an instrumentation call to my routine
  - Pass my routine two arguments: number of instructions, thread ID

```
// Pin calls this function every time a new basic block is encountered.
// It inserts a call to docount.
VOID Trace(TRACE trace, VOID *v)
{
 // Visit every basic block in the trace
 for (BBL bbl = TRACE_BblHead(trace); BBL_Valid(bbl); bbl = BBL_Next(bbl))
 {
 // Insert a call to docount for every bbl, passing the number of
instructions.

 BBL_InsertCall(bbl, IPOINT_ANYWHERE, (AFUNPTR)docount,
IARG_FAST_ANALYSIS_CALL, IARG_UINT32, BBL_NumIns(bbl), IARG_THREAD_ID,
IARG_END);
 }
}
```

# Pintool Instruction Count Output

- `$ pin -t pin/source/tools/ManualExamples/obj-intel64/inscount_tls.so -- ./paraGraph bfs -t 8 -r soc-pokec_30m.graph`
- `$ cat inscount_tls.out`

**Total number of threads = 9**

**Count[0]= 561617530**

**Count[1]= 16153**

**Count[2]= 44659367**

**Count[3]= 44863462**

**Count[4]= 44436576**

**Count[5]= 44458686**

**Count[6]= 43808683**

**Count[7]= 44055917**

**Count[8]= 43408645**

# Pin Cache Example

- ... -t source/tools/Memory/obj-intel64/dcache.so ...

- cat dcache.out

```
PIN:MEMLATENCIES 1.0. 0x0
```

```
#
```

```
DCACHE stats
```

```
#
```

```
L1 Data Cache:
```

```
Load-Hits: 131764147 59.69%
```

```
Load-Misses: 88995193 40.31%
```

```
Load-Accesses: 220759340 100.00%
```

```
#
```

```
Store-Hits: 71830273 71.07%
```

```
Store-Misses: 29242668 28.93%
```

```
Store-Accesses: 101072941 100.00%
```

```
#
```

```
Total-Hits: 203594420 63.26%
```

```
Total-Misses: 118237861 36.74%
```

```
Total-Accesses: 321832281 100.00%
```

# Pin Trace Example

- From a prior project
  - Records the instruction count
  - Records read/write and the address
- The trace was then used by a simulator

```
// Print a memory write record and the number of instructions between
// previous memory access and this access
VOID RecordMemWrite(UINT32 thread_id, VOID * addr)
{
 // format: W - [total num ins so far] - [num ins between prev mem access and this
access] - [address accessed]
 total_counts[thread_id]++;
 files[thread_id] << "W " << total_counts[thread_id] << " " << icounts[thread_id] <<
" " << addr << std::endl;
 reset_count(thread_id);
}
```



# Contech

- **Compiler-based instrumentation**
  - **Uses Clang and LLVM**
  - **Record control flow, memory accesses, concurrency**
- **Multi-language: C, C++, Fortran**
- **Multi-runtime: pthreads, OpenMP, Cilk, MPI**
- **Multi-architecture: x86, ARM**

# Contech continued

- **Designed around writing analysis not instrumentation**
  - **All instrumentation is always used**
  - **Assumes the program is correct**
  - **Traces are analyzed after collection, not during**
  
- **Sample backends (i.e., analysis tools) are available**
  - **Cache Model**
  - **Data race detection**
  - **Memory usage**

# Contech Trace Collection

- Running the instrumented program generates a trace
  - Traces are processed into taskgraphs
  - Taskgraphs store the ordering of concurrent work

## Perf Optimization I: Work Distribution and Scheduling

**Basic Cilk Plus examples**

```
// foo() and bar() may run in parallel
cilk_spawn foo();
bar();
cilk_sync;
```

```
// foo() and bar() may run in parallel
cilk_spawn foo();
cilk_spawn bar();
cilk_sync;
```

Same amount of independent work first example, but potentially higher runtime overhead (due to two spawns vs. one)

```
// foo, bar, fizz, buzz, may run in parallel
cilk_spawn foo();
cilk_spawn bar();
cilk_spawn fizz();
buzz();
cilk_sync;
```

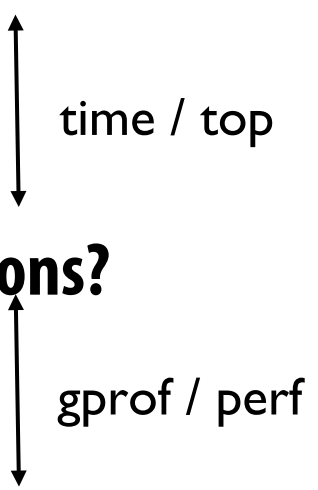
Taskgraphs

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# Contech Trace Collection Example

- `./paraGraph bfs -t 8 -r soc-pokec_30m.graph`
  - **BFS Time: 0.0215s -> 0.2108s (9.8x slowdown)**
  - **1855MB trace -> 1388MB taskgraph**
    - **91 million basic blocks**
    - **321 million memory accesses**
    - **3 million synchronization operations**

# Summary Questions

- **If you may have a performance issue:**
    - **Is the issue reproducible?**
      - **Do you have a workload?**
      - **Is the system stable?**
    - **Is the workload at full CPU?**
      - **If not, are there other users / processes running?**
      - **Or does the workload rely heavily on IO?**
    - **Is the CPU time confined to a small number of functions?**
      - **What is the most time consuming function(s)?**
      - **What is their algorithmic cost and complexity?**
- 

# Summary Continued

- **You have a reproducible, stable workload**
  - **The machine is otherwise idle**
  - **The workload is fully using its CPUs**
  - **The algorithms are appropriate**
  
- **Is there a small quantity of hot functions?**
  - **Are their cycles confined to specific functions?**
  - **Are the costs of the instructions understood?**

↑  
perf / VTune  
↓

# Instrumentation Tool Links

- Gprof - <https://sourceware.org/binutils/docs/gprof/>
- Perf - [https://perf.wiki.kernel.org/index.php/Main\\_Page](https://perf.wiki.kernel.org/index.php/Main_Page)
- VTune -  
<https://software.intel.com/en-us/qualify-for-free-software/student>
- Valgrind - <http://valgrind.org/>
- Sanitizers - <https://github.com/google/sanitizers>
- Pin -  
<https://software.intel.com/en-us/articles/pin-a-dynamic-binary-instrumentation-tool>
- Contech - <http://bprail.github.io/contech/>

# Other links

- Performance Anti-patterns:

<http://queue.acm.org/detail.cfm?id=1117403>