Single Node Optimisation

Profiling

Reusing this material

What is profiling?

- Analysing your code to find out the proportion of execution time spent in different routines.
- Essential to know this if we are going to target optimisation.
- No point optimising routines that don't significantly contribute to the overall execution time.
  - can just make your code less readable/maintainable

Code profiling

- Code profiling is the first step for anyone interested in performance optimisation
- Profiling works by instrumenting code at compile time
  - Thus it's (usually) controlled by compiler flags
  - Can reduce performance
- Standard profiles return data on:
  - Number of function calls
  - Amount of time spent in sections of code
- Also tools that will return hardware specific data
  - Cache misses, TLB misses, cache re-use, flop rate, etc…
  - Useful for in-depth performance optimisation

Sampling and tracing

- Many profilers work by sampling the program counter at regular intervals (normally 100 times per second).
  - low overhead, little effect on execution time
- Builds a statistical picture of which routines the code is spending time in.
  - if the run time is too small (< ~10 seconds) there aren't enough samples for good statistics
- Tracing can get more detailed information by recording some data (e.g. time stamp) at entry/exit to functions
  - higher overhead, more effect on runtime
  - unrestrained use can result in huge output files

Standard Unix profilers

- Standard Unix profilers are prof and gprof
- Many other profiling tools use same formats
- Usual compiler flags are **`-p`** and **`-pg`**:
  - **`ftn -p mycode.F90 -o myprog`** for prof
  - **`cc -pg mycode.c -o myprog`** for gprof
- When code is run it produces instrumentation log
  - **`mon.out`** for prof
  - **`gmon.out`** for gprof
- Then run prof/gprof *on your executable program*
  - eg. **`gprof myprog`** (*not* **`gprof gmon.out`**)

Standard profilers

- **`prof myprog`** reads **`mon.out`** and produces this:

%Time	Seconds	Cumsecs	#Calls	msec/call	Name
32.4	0.71	0.71	14	50.7	relax_
28.3	0.62	1.33	14	44.3	resid_
11.4	0.25	1.58	3	83.	__f90_close
5.9	0.13	1.71	1629419	0.0001	_mcount
5.0	0.11	1.82	339044	0.0003	__f90_slr_i4
5.0	0.11	1.93	167045	0.0007	__inrange_single
2.7	0.06	1.99	507	0.12	_read
2.7	0.06	2.05	1	60.	MAIN_

Standard profilers

- **gprof myprog** reads **gmon.out** and produces something very similar
- **gprof** also produces a program calltree sorted by inclusive times
- Both profilers list all routines, including obscure system ones
  - Of note: **mcount**(), _**mcount**(), **moncontrol**(), _**moncontrol**() **monitor**() and _**monitor**() are all overheads of the profiling implementation itself
  - _**mcount**() is called every time your code calls a function; if it's high in the profile, it can indicate high function-call overhead
  - **gprof** assumes calls to a routine from different parents take the same amount of time – may not be true

The Golden Rules of profiling

- **Profile your code**
  - The compiler/runtime will NOT do all the optimisation for you.
- **Profile your code yourself**
  - Don't believe what anyone tells you. They're wrong.
- **Profile on the hardware you want to run on**
  - Don't profile on your laptop if you plan to run on ARCHER2.
- **Profile your code running the full-sized problem**
  - The profile will almost certainly be qualitatively different for a test case.
- **Keep profiling your code as you optimise**
  - Concentrate your efforts on the thing that slows your code down.
  - This will change as you optimise.
  - So keep on profiling.

CrayPAT

- Can do both statistic sampling and function/loop level tracing.

Recommended usage:

1. Build and instrument code
2. Run code and get statistic profile
3. Re-instrument based on profile
4. Re-run code to get more detailed tracing

Example with CrayPAT

- Load performance tools software
  ~~`module load perftools-base`~~ (automatically loaded on ARCHER2)
  `module load perftools-lite`

- Re-build application (keep .o files)
  ```
  make clean
  make
  ```

- Application automatically instrumented for you

- Run the instrumented application to get top time consuming routines
  - You should get performance profiling in your Slurm output file
  - You should get a performance file `<executable_name+93500-1088s>`

Example with CrayPAT

```
CrayPat/X:  Version 20.10.0 Revision 7ec62de47  09/16/20 16:57:54
Experiment:                  lite  lite-samples
......
 Samp% | Samp | Imb. |   Imb. | Group
       |      | Samp |  Samp% |  Function=[MAX10]
       |      |      |        |   PE=HIDE
       |      |      |        |    Thread=HIDE
 100.0% | 17.8 |   -- |     -- | Total
|-----------------------------------------------------------
|  64.8% | 11.5 |   -- |     -- | ETC
||----------------------------------------------------------
||  59.2% | 10.5 |  0.5 |   6.1% | spinwait<>
||   5.6% |  1.0 |  1.0 |  66.7% | query_cpu_mask
||==========================================================
|  18.3% |  3.2 |  1.8 |  46.7% | MPI
||----------------------------------------------------------
||  18.3% |  3.2 |  1.8 |  46.7% | MPI_Barrier
||==========================================================
|   7.0% |  1.2 |   -- |     -- | USER
||----------------------------------------------------------
||   5.6% |  1.0 |  0.0 |   0.0% | checkSTREAMresults
||   1.4% |  0.2 |  0.8 | 100.0% | stream_memory_task.LOOP@li.121
||==========================================================
|   5.6% |  1.0 |  0.0 |   0.0% | RT
||----------------------------------------------------------
||   5.6% |  1.0 |  0.0 |   0.0% | nanosleep
||==========================================================
|   4.2% |  0.8 |  0.2 |  33.3% | PTHREAD
||----------------------------------------------------------
||   4.2% |  0.8 |  0.2 |  33.3% | pthread_join
|===========================================================
......

Program invocation:
  /lus/cls01095/work/z19/z19/adrianj/DistributedStream/src/./distributed_streams

For a complete report with expanded tables and notes, run:
  pat_report /lus/cls01095/work/z19/z19/adrianj/DistributedStream/src/distributed_streams+93500-1088s

For help identifying callers of particular functions:
  pat_report -O callers+src /lus/cls01095/work/z19/z19/adrianj/DistributedStream/src/distributed_streams+93500-1088s
To see the entire call tree:
  pat_report -O calltree+src /lus/cls01095/work/z19/z19/adrianj/DistributedStream/src/distributed_streams+93500-1088s

For interactive, graphical performance analysis, run:
  app2 /lus/cls01095/work/z19/z19/adrianj/DistributedStream/src/distributed_streams+93500-1088s
```

Example with CrayPAT

- Load performance tools software
  ~~`module load perftools-base`~~ (automatically loaded on ARCHER2)
  `module load perftools`

- Re-build application (keep .o files)
  ```
  make clean
  make
  ```

- Instrument application for automatic profiling analysis
  - You should get an instrumented program `a.out+pat`
  ```
  pat_build –O apa a.out
  ```

- Run the instrumented application (...+pat) to get top time consuming routines
  - You should get a performance file (“`<sdatafile>.xf`”) or multiple files in a directory `<sdatadir>`

Example with CrayPAT (2/2)

- Generate text report and an `.apa` instrumentation file
  `pat_report [<sdatafile>.xf | <sdatadir>]`
  - Inspect the `.apa` file and sampling report whether additional instrumentation is needed
    - See especially sites “Libraries to trace” and “HWPC group to collect”
- Instrument application for further analysis (a.out+apa)
  `pat_build –O <apafile>.apa`
- Run application (...+apa)
- Generate text report and visualization file (.ap2)
  `pat_report –o` ***`my_text_report.txt`*** **`<data>`**
- View report in text and/or with Cray Apprentice[2]
  `app2` ***`<datafile>`*** **`.ap2`**

Finding single-core hotspots

- Remember: pay attention only to user routines that consume significant portion of the total time
- View the key hardware counters, for example
  - L1 and L2 cache metrics
  - use of vector (SSE/AVX) instructions

- CrayPAT has mechanisms for finding “the” hotspot in a routine (e.g. in case the routine contains several and/or long loops)
  - CrayPAT API
    - Possibility to give labels to “PAT regions”
  - Loop statistics (works only with Cray compiler)
    - Compile & link with CCE using -h profile_generate
    - pat_report will generate loop statistics if the flag is enabled

```
USER / remap_
-----------------------------------------------------------------------------
  Time%                                                   25.2%
  Time                                                15.801180 secs
  Imb. Time                                            2.582609 secs
  Imb. Time%                                              14.7%
  Calls                           0.026M/sec          460,800.0 calls
  CPU_CLK_UNHALTED:THREAD_P                      77,964,376,624
  CPU_CLK_UNHALTED:REF_P                          2,689,572,161
  DTLB_LOAD_MISSES:MISS_CAUSES_A_WALK                20,626,569
  DTLB_STORE_MISSES:MISS_CAUSES_A_WALK               17,745,058
  L1D:REPLACEMENT                                 2,753,483,367
  L2_RQSTS:ALL_DEMAND_DATA_RD                     1,912,839,218
  L2_RQSTS:DEMAND_DATA_RD_HIT                     1,757,495,428
  FP_COMP_OPS_EXE:SSE_SCALAR_DOUBLE                       1,597
  FP_COMP_OPS_EXE:SSE_FP_SCALAR_SINGLE            1,556,036,610
  FP_COMP_OPS_EXE:X87                             1,878,388,524
  FP_COMP_OPS_EXE:SSE_PACKED_SINGLE                 302,976,589
  SIMD_FP_256:PACKED_SINGLE                       5,003,127,724
  User time (approx)             17.476 secs     47,202,147,918 cycles  100.0% Time
  CPU_CLK                          2.90GHz
  HW FP Ops / User time       2,556.183M/sec     44,671,354,883 ops   11.8%peak(DP)
  Total SP ops                2,448.698M/sec     42,792,964,761 ops
  Total DP ops                  107.485M/sec      1,878,390,122 ops
  MFLOPS (aggregate)         61,348.39M/sec
  D2 cache hit,miss ratio          94.4% hits              5.6% misses
  D2 to D1 bandwidth          6,680.690MiB/sec  122,421,709,963 bytes
  Average Time per Call                                0.000034 secs
  CrayPat Overhead : Time          11.4%
```

Flat profile data

HW counter values

Derived metrics

Hardware performance counters

- CrayPAT can interface with HWPCs
  - Gives extra information on how hardware is behaving
  - Very useful for understanding (& optimising) application performance
- Provides information on
  - hardware features, e.g. caches, vectorisation and memory bandwidth
- Available on per-program and per-function basis
  - Per-function information only available through tracing
- Number of simultaneous counters limited by hardware
  - 2 counters available with AMD Rome processors
  - If you need more, you'll need multiple runs
- Most counters accessed through the PAPI interface
  - Either native counters or derived metrics constructed from these

Hardware counters selection

- HWPCs collected using CrayPAT
  - Compile and instrument code for profiling as before
- Set PAT_RT_PERFCTR environment variable at runtime
  - e.g. in the job script
    - Hardware counter events are not collected by default (except with APA)
- `export PAT_RT_PERFCTR=...`
  - either a list of named PAPI counters
  - or `<set number>` = a pre-defined (and useful) set of counters
    - recommended way to use HWPCs
    - there are 8 groups to choose from
      - To see them:
        - `pat_help -> counters -> rome -> groups`
        - `man hwpc`
        - More `/opt/cray/pe/perftools/20.10.0/share/counters/CounterGroups.amd_fam23mod49`

Technical term for AMD Rome

Predefined AMD Rome HW Counter Groups

0: Summary with translation lookaside buffer activity

1: Summary with branch activity

default: mem_bw

default_samp: default

mem_bw: memory bandwidth

mem_bw_1: memory load bandwidth, stalls

mem_bw_2: memory load bandwidth, cycles

stalls: Dispatch stalls for load, store, fp

Example: mem_bw

```
 USER / sweepy_
-----------------------------------------------------------------------------
  Time%                                                 14.6%
  Time                                               8.738150 secs
  Imb. Time                                          3.077320 secs
  Imb. Time%                                            27.2%
  Calls                     11.547 /sec                 100.0 calls
  CPU_CLK_UNHALTED:THREAD_P                    92,754,888,918
  CPU_CLK_UNHALTED:REF_P                        2,759,876,135
  L1D:REPLACEMENT                               1,813,741,166
  L2_RQSTS:ALL_DEMAND_DATA_RD                   1,891,459,700
  L2_RQSTS:DEMAND_DATA_RD_HIT                   1,644,133,800
  LLC_MISSES                                       98,952,928
  LLC_REFERENCES                                  690,626,471
  User time (approx)         8.660 secs        23,390,899,520 cycles  100.0% Time
  CPU_CLK                     3.36GHz
  D2 cache hit,miss ratio  86.4% hits                   13.6% misses
  L3 cache hit,miss ratio  85.7% hits                   14.3% misses
  D2 to D1 bandwidth  13,330.757MiB/sec       121,053,420,792 bytes
  Average Time per Call                              0.087381 secs
  CrayPat Overhead : Time   0.0% ….
```

Interpreting the performance numbers

- Performance numbers are an average over all ranks
  - explains non-integer values
- This does not always make sense
  - e.g. if ranks are not all doing the same thing:
    - Master-slave schemes
    - MPMD apruns combining multiple, different programs
- Want them to only process data for certain ranks
  - `pat_report -sfilter_input='condition' ...`
  - `condition` should be an expression involving pe, e.g.
    - `pe<1024` for the first 1024 ranks only
    - `pe%2==0` for every second rank

OpenMP data collection and reporting

- Give finer-grained profiling of threaded routines
  - Measure overhead incurred entering and leaving
    - Parallel regions
      - #pragma omp parallel
    - Work-sharing constructs within parallel regions
      - #pragma omp for

- Timings and other data now shown per-thread
  - rather than per-rank

- OpenMP tracing enabled with `pat_build -gomp ...`
  - CCE: insert tracing points around parallel regions automatically
  - AMD, Gnu: need to use CrayPAT API manually

OpenMP data collection and reporting

- Load imbalance for hybrid MPI/OpenMP programs
  - now calculated across all threads in all ranks
  - imbalances for MPI and OpenMP combined
    - Can choose to see imbalance in each programming model separately
- Data displayed by default in pat_report
  - no additional options needed
  - Report focuses on where program is spending its time
  - Assumes all requested resources should be used
    - you may have reasons not to want to do this, of course

Memory usage

- Knowing how much memory each rank uses is important:
  - What is the minimum number of cores I can run this problem on?
    - given there is 256GB (~254GB usable) of memory per node (128 cores)
  - Does memory usage scale well in the application?
  - Is memory usage balanced across the ranks in the application?
  - Is my application spending too much time allocating and freeing?

Heap statistics

Memory per rank
~62GB usable memory per node

Too many allocs/frees?
Would show up as ETC time in CrayPAT report

Memory leaks
Not usually a problem in HPC

```
Notes for table 5:

  Table option:
    -O heap_hiwater
  Options implied by table option:
    -d am@,ub,ta,ua,tf,nf,ac,ab -b pe=[mmm]

  This table shows only lines with Tracked Heap HiWater MBytes > 0.


Table 5:  Heap Stats during Main Program

 Tracked |  Total |  Total |  Tracked |  Tracked |PE[mmm]
    Heap | Allocs |  Frees |  Objects |   MBytes |
 HiWater |        |        |      Not |      Not |
  MBytes |        |        |    Freed |    Freed |

   9.794 |    915 |    910 |        4 |    1.011 |Total
|-----------------------------------------------------
|    9.943 |   1170 |   1103 |       68 |    1.046 |pe.0
|    9.909 |    715 |    712 |        3 |    1.010 |pe.22
|    9.446 |   1278 |   1275 |        3 |    1.010 |pe.43
|=====================================================
```

Summary

- Profiling is essential to identify performance bottlenecks
  - even at single core level
- CrayPAT has some very useful extra features
  - can pinpoint and characterise the hotspot loops (not just routines)
  - hardware performance counters give extra insight into performance
  - well-integrated view of hybrid programming models
    - most commonly MPI/OpenMP
    - also CAF, UPC, SHMEM, pthreads, OpenACC, CUDA
  - information on memory usage
- And remember the Golden Rules
  - including the one about not believing what anyone tells you