Cycle Accurate Profiling With Perf

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The plan

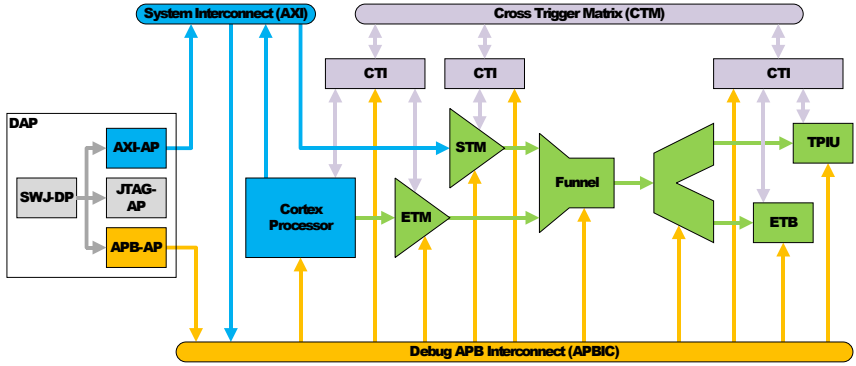
The plan

- Hardware
- Linux perf
- Let's hack!

Hardware

ARM

ARM CoreSight



- Source
- Bus
- Sink

ARM

Processor trace

- Embedded Trace Macrocell
  - Instructions
  - Data
- Program Trace Macrocell
  - Only branches
- Bandwidth
  - From 10Mbps to many Gbps per core
- Non- (or low-) intrusive debug

Sinks

- Embedded Trace Buffer
  - Dedicated, small SRAM
  - Flight recorder use case
- Trace Port
  - External analyser
  - Large buffer
  - External (high speed) pins
- Embedded Trace Router
  - Sinks data into main interconnect
  - Usually uses system DRAM
  - Consumes memory system bandwidth

ETM Protocol

- Highly compressed data
  - Generated against program memory
- Based on E/N atoms
  - eg. `b1NEEEE00` up to 16+1 instructions
- Branches
  - Only if not evident (eg. `eg. B <imm>`)
  - No address == previous address
  - Exceptions, instruction sets, processor state
- Synchronisation packets
- Data packets
- PTM protocol
  - One bit per conditional branch

Issues

- Requires memory contents for decompression
  - Multitasking OS
  - JIT engines
  - Self-modifying code (kernel runtime patching, kprobes, dynamic trace events)
- Parallel and out-of-order excecution

Additional features

- Filtering
  - Address
  - CONTEXTID
  - VMID
- Trigerring
  - Address
  - `DBG <imm>`
  - Counter
  - Sequencer
- Timestamping
  - Correlation (synchronisation)

Linux perf

Linux perf framework

- PMU drivers
- Many use cases, eg. statistics
- Sampling profiler
  - Periodic PC (IP) sampling
  - Timer or PMU counter overflow interrupt
  - Typical sampling rate 1kHz (every 1ms)

Sampling profile

- Statistical approximation of a process
- Think analog/digital converter
- Shannon's theorem: *"If a function x(t) contains no frequencies higher than B cps, it is completely determined by giving its ordinates at a series of points spaced 1/(2B) seconds apart."*

CoreSight Linux framework

- Developed by Mathieu Poirier at Linaro
- Based on 2012 code from Code Aurora
- At v7 stage now (`http://lwn.net/Articles/614232/`)
- Control trace components via `sysfs`
  - Enable sink, enable source, dump buffer contents
- Separate decoders
- Full series at `http://git.linaro.org/kernel/coresight.git`

Intel PT

- *"an exciting new feature coming in future processors"* (2013)
- Integrating with perf
  - Auxiliary buffers
  - Decoder integrated with user space tool
- Kernel portions at v4 stage now (`http://lwn.net/Articles/609010/`)
- Full series at
  `https://github.com/virtuoso/linux-perf/tree/intel_pt`

Let's hack!

Particularly pathologic example

- Rotate JPEG file

```
/ # time taskset 4 ./gm convert -rotate 90 in.jpg  out.jpg
real    0m 0.01s
user    0m 0.01s
sys     0m 0.00s
```

Can it go faster?

```
/ # time perf record -F 1000 -e cpu-clock \
        taskset 4 ./gm convert -rotate 90 in.jpg out.jpg
[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.001 MB perf.data (~50 samples) ]
real    0m 0.27s
user    0m 0.14s
sys     0m 0.13s
```

- It was:

```
real    0m 0.01s
user    0m 0.01s
sys     0m 0.00s
```

Report

```
# Samples: 17  of event 'cpu-clock'
# Event count (approx.): 17000000
#
# Overhead  Command      Shared Object                     Symbol
# ........  .......  .................  .....................
#
    17.65%       gm  [kernel.kallsyms]  [k] filemap_map_pages
     5.88%  taskset  [kernel.kallsyms]  [k] filemap_map_pages
     5.88%       gm  gm                 [.] LocaleCompare
     5.88%       gm  gm                 [.] forward_DCT_float
     5.88%       gm  gm                 [.] encode_mcu_huff
     5.88%       gm  gm                 [.] ycc_rgb_convert
     5.88%       gm  gm                 [.] decode_mcu_DC_first
     5.88%       gm  gm                 [.] decode_mcu_AC_refine
```

Report, cont.

```
5.88%    gm  gm                  [.] jpeg_fdct_16x16
5.88%    gm  gm                  [.] _IO_link_in
5.88%    gm  gm                  [.] malloc
5.88%    gm  gm                  [.] strncpy
5.88%    gm  [kernel.kallsyms]   [k] lock_acquire
5.88%    gm  [kernel.kallsyms]   [k] lock_release
5.88%    gm  [kernel.kallsyms]   [k] unmap_single_vma
```

Let's have a closer look...

- Cortex-A7 ETM 3.5
- Instructions only
- Cycle accurate
- Captured with DStream & ARM DS-5
- 10MB of binary trace data

What can we see there?

- Decoded into text format
- 890MB file
- What to look for:

```
ELF Header:
  Entry point address:                0x96dd

  8360: 000096dd     0 FUNC    GLOBAL DEFAULT    6 _start

  8845: 0012ac44     0 FUNC    GLOBAL DEFAULT    9 _fini
```

Here we go

```
2859224 S:0x8000E4CC E28DD00C  0 ADD  sp,sp,#0xc    ret_to_user_from_i
2859225 S:0x8000E4D0 E1B0F00E  1 MOVS pc,lr  ret_to_user_from_irq
                                Return from exception
                                Timestamp: 1878241989137
        S:0x000096DC F04F0B00 29 MOV  r11,#0 <Unknown>
                                Exception: PREFETCH_ABORT (11)
2859227 S:0xFFFF000C EA000443 21 B   PRRR+16027512 ; 0xFFFF1120    <Un
                                Timestamp: 1878241989138
2859228 S:0xFFFF1120 E24EE004 18 SUB  lr,lr,#4       <Unknown>
2859229 S:0xFFFF1124 E88D4001  3 STM  sp,r0,lr     <Unknown>
```

Here we go again

```
2878794 S:0x8000E4D0 E1B0F00E  1 MOVS    pc,lr ret_to_user_from_irq
                               Return from exception
                               Timestamp: 1878241990817
2878795 S:0x000096DC F04F0B00 175 MOV  r11,#0 <Unknown>
2878796 S:0x000096E0 F04F0E00  40 MOV  lr,#0  <Unknown>
2878797 S:0x000096E4 BC02       4 POP  r1    <Unknown>
2878798 S:0x000096E6 466A       1 MOV  r2,sp  <Unknown>
[...]
2878804 S:0x000096F6 4B04     1 LDR  r3,[pc,#16] ; [0x9708] = 0xB11468
2878805 S:0x000096F8 F0DAFDF4  0 BL   __libc_start_main ; 0xE42E4   <U
     S:0x000E42E4 E92D45F0 324 PUSH r4-r8,r10,lr __libc_start_main
                               Exception: PREFETCH_ABORT (11)
2878807 S:0xFFFF000C EA000443  21 B    PRRR+16027512 ; 0xFFFF1120    <U
```


ARM

Going down

```
9747820 S:0x0012AC44 E91D4008 153 PUSH r3,lr        <Unknown>
9747821 S:0x0012AC48 E8BD8008   2 POP  r3,pc        <Unknown>
9747822 S:0x000E9AA2 E7BF     9 B   __run_exit_handlers+28 ; 0xE9A24
9747823 S:0x000E9A24 6873     3 LDR  r3,[r6,#4]    __run_exit_handlers
9747824 S:0x000E9A26 EB061403  3 ADD  r4,r6,r3,LSL #4      __run_exit_
9747825 S:0x000E9A2A B173     1 CBZ  r3,__run_exit_handlers+66 ; 0xE9A
```

The end of the process

```
9747990 S:0x000FD536 4C12    2 LDR  r4,[pc,#72] ; [0xFD580] = 0x64C55B3
9747991 S:0x000FD538 E004    0 B    _Exit+24 ; 0xFD544    _Exit
9747992 S:0x000FD544 4618    1 MOV  r0,r3  _Exit
9747993 S:0x000FD546 F04F0CF8 1 MOV  r12,#0xf8      _Exit
9747994 S:0x000FD54A F7E7F9C9 0 BL   __libc_do_syscall ; 0xE48E0   _Ex
9747995 S:0x000E48E0 B580    1 PUSH r7,lr      __libc_do_syscall
9747996 S:0x000E48E2 4667    2 MOV  r7,r12 __libc_do_syscall
9747997 S:0x000E48E4 DF00    1 SVC  #0x0   __libc_do_syscall
                             Exception: SUPERVISOR_CALL (10)
```

- #0xf8 is __NR_exit_group

Focus on the task

- It's all interesting...
- ...but the goal is to see a cycle accurate profile of the process
- Limit data scope
  - Filter out kernel addresses (or cheat using entry/exit points)
  - Filter out other contexts (or cheat by protecting CPU)
  - Collate migrated data (or cheat by setting affinity)
  - Generate memory map with DSOs (or cheat by linking statically)
- Convert into perf data stream

perf.data

- Starts with header
- Description of all events
- Followed by data records ...
  - selection of samples
  - by default: `PERF_SAMPLE_IP`, `PERF_SAMPLE_TID`, `PERF_SAMPLE_TIME`, `PERF_SAMPLE_PERIOD`
  - generated on every timer/counter interrupt
- ...interleaved with system information
  - eg. `PERF_RECORD_MMAP`, `PERF_RECORD_COMM`, `PERF_RECORD_EXIT`, `PERF_RECORD_FORK`

perf.data, cont.

```
$ perf report -D
[...]
0x1d0 [0x28]: event: 9
.
. ... raw event: size 40 bytes
.  0000:  09 00 00 00 01 00 28 00 54 fd 05 80 00 00 00 00  ......(.T.......
.  0010:  3b 08 00 00 3b 08 00 00 46 fb 39 91 dd 46 00 00  ;...;...F.9..F..
.   0020:  40 42 0f 00 00 00 00 00                          @B......
.
77917438212934 0x1d0 [0x28]: PERF_RECORD_SAMPLE(IP, 1): \
        2107/2107: 0x8005fd54 period: 1000000 addr: 0
 ... thread: gm:2107
  ...... dso: [kernel.kallsyms]
```

The Hack

- Replace data records with trace-based ones
  - reducing number of samples, from 40 to 24 bytes per record (attribute modification needed)
  - generating multiple samples, one per cycle used (175 samples if instruction took 175 cycles to execute)
- 192MB big `perf.data`

The Hack, cont.

```
0x1f0 [0x18]: event: 9
. ... raw event: size 24 bytes
. 0000:  09 00 00 00 02 00 18 00 dc 96 00 00 00 00 00 00  ................
. 0010:  3b 08 00 00 3b 08 00 00                          ;...;...
0x1f0 [0x18]: PERF_RECORD_SAMPLE(IP, 2): \
        2107/2107: 0x96dc period: 1 addr: 0
 ... thread: :2107:2107
  ...... dso: <not found>
  0x208 [0x18]: event: 9
  . ... raw event: size 24 bytes
  . 0000:  09 00 00 00 02 00 18 00 dc 96 00 00 00 00 00 00  ................
  . 0010:  3b 08 00 00 3b 08 00 00                          ;...;...
  0x208 [0x18]: PERF_RECORD_SAMPLE(IP, 2): \
          2107/2107: 0x96dc period: 1 addr: 0
   ... thread: :2107:2107
```


ARM

Result

```
# Samples: 8M of event 'cycles'
# Event count (approx.): 8012563
#
# Overhead  Command    Shared Object                          Symbol
# ........  .......  ...............  ..............................
#
     8.98%       gm  gm                [.] jpeg_idct_islow
     7.25%       gm  gm                [.] strncpy
     6.60%       gm  gm                [.] jpeg_fdct_16x16
     4.40%       gm  gm                [.] encode_mcu_huff
     4.37%       gm  gm                [.] decode_mcu_AC_refine
     4.25%       gm  gm                [.] LocaleCompare
     3.73%       gm  gm                [.] rgb_ycc_convert
     3.25%       gm  gm                [.] _int_free
```

Result, cont

```
  3.17%        gm  gm                 [.] memset
  3.15%       gm  gm                [.] jpeg_gen_optimal_table
  3.01%        gm  gm                 [.] malloc
  2.63%        gm  gm                 [.] _int_malloc
  2.63%        gm  gm                 [.] forward_DCT_float
  2.59%        gm  gm                 [.] ycc_rgb_convert
  2.43%        gm  gm                 [.] jpeg_fdct_float
 2.29%     gm  gm             [.] __pthread_mutex_unlock_usercnt
  2.25%        gm  gm                 [.] __memcpy_neon
  2.19%        gm  gm                 [.] pthread_mutex_lock
  1.74%        gm  gm                 [.] ReadJPEGImage
  1.72%        gm  gm                 [.] encode_mcu_gather
  1.61%        gm  gm                 [.] WriteJPEGImage
  1.39%        gm  gm                 [.] vfprintf
```

Result, cont

```
 1.32%        gm  gm                [.] consume_data
 1.21%        gm  gm                [.] forward_DCT
 1.06%        gm  gm                [.] RegisterMagickInfo
 0.88%        gm  gm               [.] UnregisterMagickInfo
 0.87%        gm  gm                [.] decode_mcu_AC_first
 0.81%        gm  gm                [.] strlen
 0.73%        gm  gm                [.] SyncCacheNexus
 0.64%        gm  gm                [.] strcpy
 0.53%        gm  gm               [.] jpeg_fill_bit_buffer
 0.49%        gm  gm                [.] decode_mcu_DC_first
 0.40%        gm  gm                [.] _IO_default_xsputn
 0.35%        gm  gm                [.] _init
 0.34%       gm  gm              [.] jpeg_make_d_derived_tbl
 0.33%        gm  gm                [.] DestroyMagickInfo
```

Result, cont

0.33%	gm	gm	[.] QueryColorDatabase
0.32%	gm	gm	[.] GetGeometry
0.31%	gm	gm	[.] SetNexus
0.31%	gm	gm	[.] free
0.29%	gm	gm	[.] __strchrnul
0.27%	gm	gm	[.] ____strtod_l_internal
0.27%	gm	gm	[.] .divsi3_skip_div0_test
0.24%	gm	gm	[.] SetCacheNexus
0.23%	gm	gm	[.] access_virt_barray
0.23%	gm	gm	[.] compress_output
0.22%	gm	gm	[.] ____strtol_l_internal
0.21%	gm	gm	[.] UnlockSemaphoreInfo
0.21%	gm	gm	[.] AcquireCacheNexus
0.21%	gm	gm	[.] format_message

Result, cont

```
[...]
```

Result, cont

```
 0.00%   gm  gm   [.] ___fini_from_thumb
 0.00%   gm  gm   [.] jpeg_destroy_compress
 0.00%   gm  gm   [.] __feupdateenv
 0.00%   gm  gm   [.] IdentityAffine
 0.00%   gm  gm   [.] __dcgettext
 0.00%   gm  gm   [.] _setjmp
 0.00%   gm  gm   [.] DestroyMagickResources
 0.00%   gm  gm   [.] jpeg_free_small
 0.00%   gm  gm   [.] fprintf
 0.00%   gm  gm   [.] DestroySemaphore
 0.00%   gm  gm   [.] jpeg_mem_term
 0.00%   gm  gm   [.] start_pass_downsample
 0.00%   gm  gm   [.] malloc_info
 0.00%   gm  gm   [.] __stpcpy
```

Result, cont

- 616 lines of report
- `perf annotate` works as well!

Summary

Summary

- Proof of concept
- Can help with pathological cases
- Scaling issues
- Powerful but need to by “civilised”
- Nearest future
  - Drivers in mainline
  - perf tool decoder integration

Thank You

ARM