Optimizing the Software Stack of a Cosmic Proportions Cluster of Multi-Core Machines

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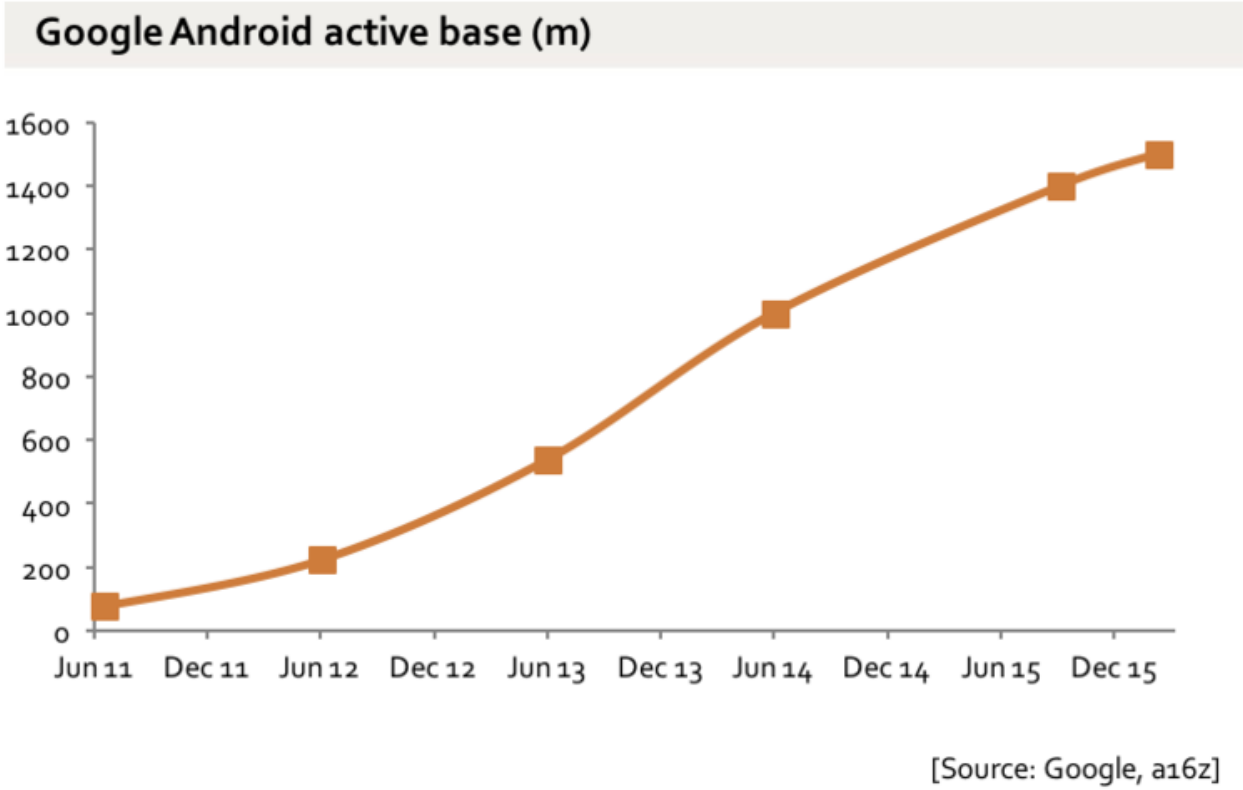
Android: a Cosmic Sized Cluster

- top500: $10M$ cores / $15.3MW$ [1] / US$273 million [2]
- Android devices: $\sim 6B$ cores [3] / $\sim 300MW$ [4] / $\sim$ US$0



[Source: Google, a16z]

[1] https://www.top500.org/lists/2016/11

[2] https://en.wikipedia.org/wiki/Sunway_TaihuLight

[3] 4 cores / device

[4] battery $13.2Wh = 4.4V * 3000mAh$, charging every 48 hours

Android Open Source Project (AOSP) Software Stack

- AOSP: common base for Android devices (+ customization)
- C/C++ for the platform libraries, Java for user interface

ansic	22 MLoC	39%
cpp	13 MLoC	23%
java	10 MLoC	17%

- $\sim$ 80% execution cycles in C/C++, $\sim$ 20% in Java [5]

[5] Linux-perf profile of my own usage of an Android device.

[6] Data collected during a 7-day period ending on January 9, 2017.

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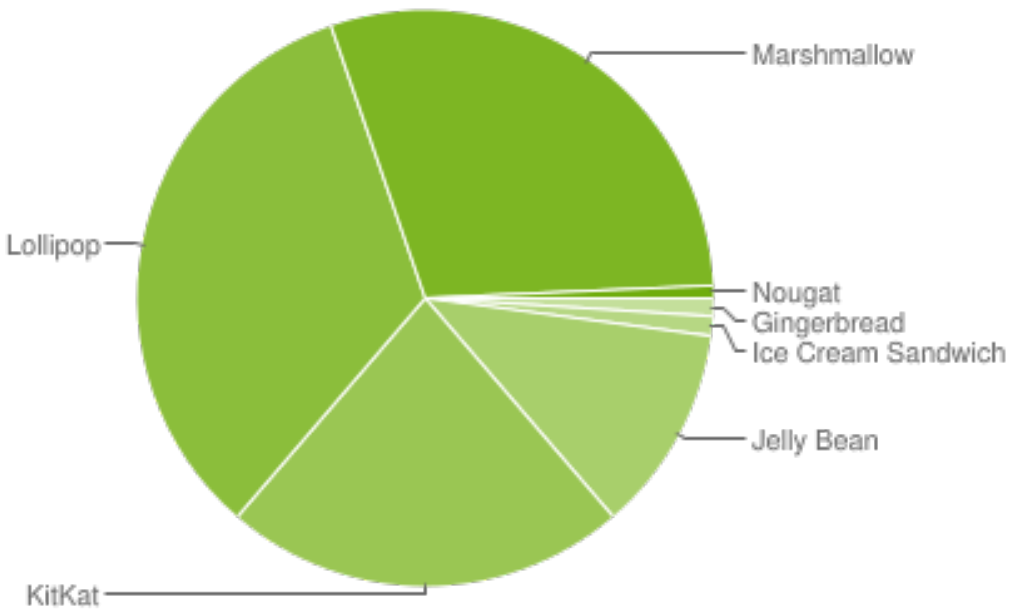
- release/updates/deprecation (5 $\sim$ 6 years)



[6]

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Why Optimizing the Performance of Android?

Why bothering?

- the code of Android is cold (flat profile), full of branches
- there are few loops (image processing, compression, etc.)

[7] $\$0.12/kWh$, battery $13.2Wh = 4.4V * 3000mAh$, charging every 48 hours

Why Optimizing the Performance of Android?

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Motivation:

- same code executed billions of time
- outer loop is outside the device $\rightarrow$
  - improve innermost scalar code
  - profile how often code is in use
  - variation over time following popularity of apps
  - continuously monitor usage patterns
  - tune code optimization over time

\$0.30 / device / year $\longrightarrow$ \$300M / billion devices / year [7]

[7] \$0.12/kWh, battery $13.2Wh = 4.4V * 3000mAh$, charging every 48 hours

Agenda

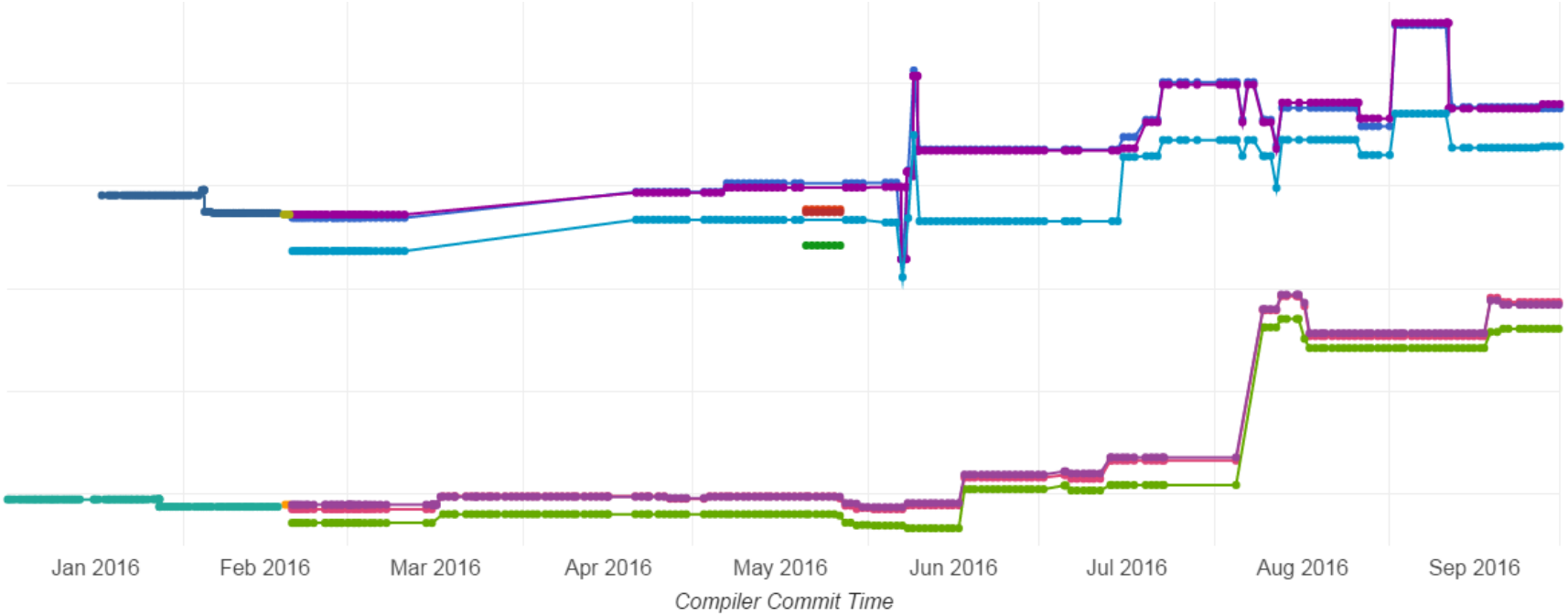
- tools for performance analysis
- improve performance of AOSP libraries
- enable continuous profiling and optimization (AutoFDO)
- enable more secure execution environments (CFI)

Performance Analysis

- benchmarks
- Linux perf
- Valgrind
- static profiles

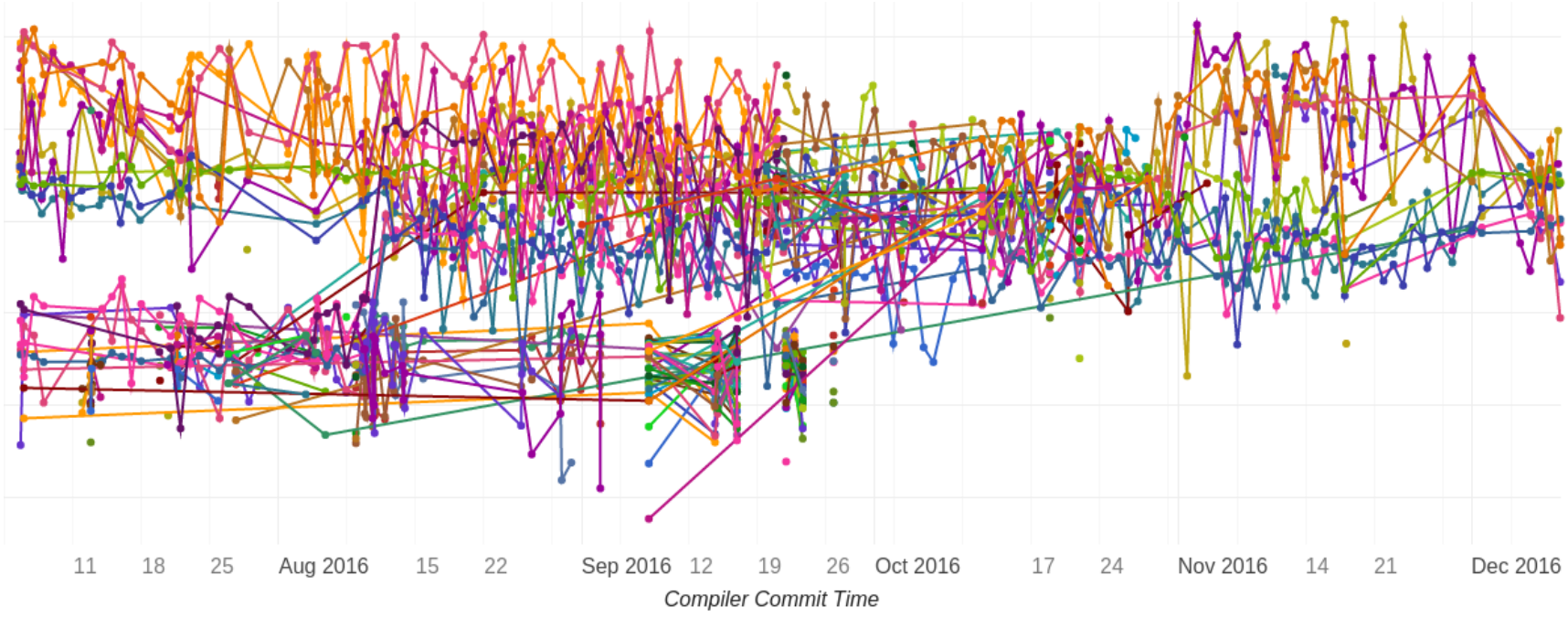
Benchmarks

track performance (compiler/libraries) over time



Benchmarks

on a real device (and a noisy benchmark...)



Performance Analysis with Valgrind

- `valgrind [--tool=memcheck]`
  valgrind mostly known for its memory leak checker
- `valgrind --tool=cachegrind`
  - cache and branch simulator
  - count read, write, and branch instructions
  - **SARC contribution**: diff tool for cachegrind profiles [8]
- `valgrind --tool=callgrind`
  - execution call graph
  - visualization tool kcachegrind

[8] `https://github.com/bmrzycki/cg_difftext`

Valgrind: Example – SQLite

```
$ valgrind --tool=cachegrind ./sqlite_llvm <test.sql >/dev/null
[...]
--------------------------------------------------------------------------------
           Ir       I1mr   ILmr          Dr      D1mr    DLmr          Dw      D1mw    DLmw
--------------------------------------------------------------------------------
1,278,771,731 29,231,219 35,783 359,414,267 6,707,514 528,920 197,515,528 2,594,262 171,968  PROGRAM TOTALS

--------------------------------------------------------------------------------
         Ir      I1mr  ILmr         Dr      D1mr    DLmr         Dw    D1mw   DLmw  file:function
--------------------------------------------------------------------------------
363,052,233 7,560,087 3,122 97,707,865 1,084,529  77,197 44,505,055 217,826 29,838  src/sqlite3.c:sqlite3VdbeExec
 95,048,357    80,721   111 33,248,107    59,086   7,273 20,173,275      91      7  src/sqlite3.c:vdbeRecordCompareWithSkip
 68,045,026   695,509 1,144 14,883,933   114,698   1,918  5,525,733 272,507 19,249  src/sqlite3.c:balance
 56,713,554 1,101,002   276 18,416,705   683,914  21,085  3,453,665   1,947     25  src/sqlite3.c:sqlite3BtreeMovetoUnpacked
 45,344,891    59,660    66 13,589,490    66,121  18,775 12,795,281  59,451     86  src/sqlite3.c:sqlite3VdbeRecordUnpack
 36,550,248    47,192    94  9,615,816   217,845  11,567          0       0      0  src/sqlite3.c:cellSizePtr
 35,156,491 1,031,905   859  7,810,853   489,509   1,936  6,546,085 175,469 26,159  /build/glibc-2.19/malloc/malloc.c:_int_malloc
 34,402,967   219,015    40 12,316,213    31,625   1,007          0       0      0  src/sqlite3.c:vdbeRecordCompareInt
 31,287,698   269,233   121 10,094,976   398,015  57,982 10,094,976 797,005 41,768  /build/glibc-2.19/string/../ports/sysdeps/aarch64/memcpy.S:mem
 30,895,222 1,055,479   718  3,990,072    45,246     157  3,247,672   1,200     58  src/sqlite3.c:sqlite3VXPrintf
 29,633,734        87    87  6,992,348   510,654 147,437  1,945,350     292     14  src/sqlite3.c:vdbeSorterSort
 28,301,654 1,222,726   236  7,685,792   129,350     101  4,693,862  15,480     91  src/sqlite3.c:sqlite3BtreeInsert
 27,452,670   605,975   428  7,719,336   275,711   3,045  6,130,240   1,247    180  /build/glibc-2.19/malloc/malloc.c:_int_free
 26,152,338    93,230    53  5,107,641    26,455      59  3,502,857   6,705      2  src/sqlite3.c:sqlite3VdbeSerialGet
 21,638,172   664,339   241  7,621,765   197,153   7,033  5,509,634  12,988     53  src/sqlite3.c:sqlite3PagerAcquire
 19,904,842   811,018   134  6,875,142    93,695     809  4,223,778   6,655     72  src/sqlite3.c:insertCell
 17,184,877   622,046   254  5,927,277   207,045     101  3,228,818  13,564     78  src/sqlite3.c:pager_write
 16,511,495   127,072    29  5,189,327     7,164   1,105  2,358,785       0      0  src/sqlite3.c:serialGet
 14,566,464   347,254   101  5,076,192    68,798   4,135  3,972,672 131,226  9,179  src/sqlite3.c:moveToChild
 14,089,915   528,334   433  3,522,612   169,118     295      1,089      24     22  ???:???
 13,516,049   315,369    75  3,660,565    70,941     104  2,252,728   2,740     20  /build/glibc-2.19/malloc/malloc.c:malloc
 13,444,711   370,614    60  3,136,255    74,755  57,116  3,757,149       0      0  src/sqlite3.c:btreeParseCellPtr
 11,814,468   620,489   364  3,444,231   109,318     159  1,401,768  11,253      7  src/sqlite3.c:sqlite3VdbeHalt
  9,867,819   655,851   130  3,350,976    68,237      46  1,820,276  62,050     70  src/sqlite3.c:moveToRoot
  9,023,249   615,625   175  2,774,458    27,649      72  1,719,012     578      1  src/sqlite3.c:sqlite3VdbeMemGrow
  9,015,155   136,420   114  2,528,161    33,460      40  1,808,361      12      7  /build/glibc-2.19/nptl/pthread_mutex_lock.c:pthread_mutex_lock
  8,932,696   193,491    71  1,956,326    55,921      22  1,411,634       2      0  /build/glibc-2.19/nptl/pthread_mutex_unlock.c:__pthread_mutex_
  8,916,165    82,925    47  2,092,310         0       0  1,933,573   1,583      3  src/sqlite3.c:memjrnlWrite
  8,869,488   284,528    72  4,276,902   299,688   8,315  1,834,026   6,712     17  src/sqlite3.c:pcache1Fetch
  8,120,421   171,173   145          0         0       0  4,459,287 446,962 23,788  /build/glibc-2.19/string/../ports/sysdeps/aarch64/memset.S:mem
  7,759,659   338,888    58  2,364,882    24,321   1,308  1,624,112 104,416  1,631  src/sqlite3.c:sqlite3PcacheRelease
  6,799,934    97,805   282  2,068,211    38,793     684  1,555,697   3,672     11  src/sqlite3.c:sqlite3BtreeNext
  6,674,044    88,515   123  1,706,065     4,244      43  1,094,451       7      0  src/sqlite3.c:freeSpace
  6,536,765   760,083   320  2,119,849   121,314      85  1,091,200       0      0  src/sqlite3.c:sqlite3_step
```

Valgrind: Example – SQLite

```
$ cg_difftext.py cachegrind.out.gcc cachegrind.out.llvm
[file_a] cachegrind.out.gcc
[file_b] cachegrind.out.llvm
    Ir:      1,210,101,457      1,278,770,879  [        68,669,422]
  I1mr:         23,202,418         29,231,219  [         6,028,801]
  ILmr:             30,817             35,783  [             4,966]
    Dr:        337,329,529        359,414,081  [        22,084,552]
  D1mr:          6,107,672          6,707,514  [           599,842]
  DLmr:            522,450            528,920  [             6,470]
    Dw:        180,346,394        197,515,342  [        17,168,948]
  D1mw:          2,646,481          2,594,262  [           -52,219]
  DLmw:            172,947            171,968  [              -979]

[func] sqlite3VdbeExec
[file] src/sqlite3.c
    Ir:        305,641,560        363,052,233  [        57,410,673]
  I1mr:          4,725,208          7,560,087  [         2,834,879]
  ILmr:              2,215              3,122  [               907]
    Dr:         84,047,121         97,707,865  [        13,660,744]
  D1mr:            694,519          1,084,529  [           390,010]
  DLmr:             67,617             77,197  [             9,580]
    Dw:         29,174,474         44,505,055  [        15,330,581]
  D1mw:            170,442            217,826  [            47,384]
  DLmw:             29,600             29,838  [               238]
[...]
```

Performance Analysis with Linux Perf

Two modes of operation:

- sum up all counters: `perf stat`
- record events: `perf record`

Linux Perf: Example – SQLite

```
 $ perf stat ./sqlite_llvm <test.sql >/dev/null

Performance counter stats for './sqlite_llvm':

      1045.856070      task-clock (msec)         #    1.000 CPUs utilized
                1      context-switches          #    0.001 K/sec
                0      cpu-migrations            #    0.000 K/sec
              809      page-faults               #    0.774 K/sec
    1,636,720,010      cycles                    #    1.565 GHz                      [83.16%]
      548,530,227      stalled-cycles-frontend   #   33.51% frontend cycles idle     [83.16%]
      218,991,051      stalled-cycles-backend    #   13.38% backend  cycles idle     [67.04%]
    3,385,841,295      instructions              #    2.07  insns per cycle
                                                 #    0.16  stalled cycles per insn [83.54%]
      709,436,490      branches                  #  678.331 M/sec                    [83.54%]
        2,586,354      branch-misses             #    0.36% of all branches          [83.17%]

      1.045918998 seconds time elapsed
```

Linux Perf: Example – 483.xalancbmk

```
$ perf record ./xalancbmk
$ perf report
  0.20 629a84:   ldr    w9, [x0,#24]
 18.71 629a88:   ldr    w8, [x1,#24]
 12.93 629a8c:   cmp    w9, w8
  2.74 629a90:   b.ne   629af8 <xalanc_1_8::XalanDOMString::equals
  2.00 629a94:   ldp    x8, x10, [x0]
  2.43 629a98:   cmp    x8, x10
  1.80 629a9c:   ldp    x10, x12, [x1]
  1.03 629aa0:   adrp   x11, 704000 <vtable for xalanc_1_8::ReusableArenaBlock+0x8>
  0.53 629aa4:   add    x11, x11, #0xb08
  0.03 629aa8:   csel   x8, x11, x8, eq
  1.33 629aac:   cmp    x10, x12
  0.34 629ab0:   csel   x10, x11, x10, eq
  1.78 629ab4:   cbz    w9, 629b00 <xalanc_1_8::XalanDOMString::equals
  0.02 629ab8:   ldrh   w11, [x8]
  4.02 629abc:   ldrh   w12, [x10]
  3.75 629ac0:   cmp    w11, w12
  1.03 629ac4:   b.ne   629b08 <xalanc_1_8::XalanDOMString::equals
  1.16 629ac8:   lsl    x9, x9, #1
       629acc:   add    x8, x8, #0x2
       629ad0:   add    x10, x10, #0x2
       629ad4:   sub    x9, x9, #0x2
 10.18 629ad8:   cbz    x9, 629b00 <xalanc_1_8::XalanDOMString::equals
  0.01 629adc:   ldrh   w11, [x8],#2
 18.79 629ae0:   sub    x9, x9, #0x2
  0.00 629ae4:   ldrh   w12, [x10],#2
  9.22 629ae8:   cmp    w11, w12
  5.11 629aec:   b.eq   629ad8 <xalanc_1_8::XalanDOMString::equals
       629af0:   mov    w0, wzr
       629af4:   ret
  0.69 629af8:   mov    w0, wzr
  0.09 629afc:   ret
       629b00:   orr    w0, wzr, #0x1
  0.10 629b04:   ret
       629b08:   mov    w0, wzr
       629b0c:   ret
```

Static Profiles

- information known at compile time
- decisions made by the compiler

- -flto: static call-graph
- estimated frequencies per call / basic block
- -mllvm -stats
  - register spills
  - redundancies eliminated
  - functions inlined

Static Profiles: Example

```
$ clang sort.c -c -O3 -mllvm -stats
===-------------------------------------------------------------------------===
                          ... Statistics Collected ...
===-------------------------------------------------------------------------===

   158 asm-printer      - Number of machine instrs printed
   176 basicaa          - Number of times a GEP is decomposed
     2 branchfolding    - Number of dead blocks removed
     1 branchfolding    - Number of block tails merged
     3 build-libcalls   - Number of arguments inferred as nocapture
     1 build-libcalls   - Number of functions inferred as nounwind
     1 build-libcalls   - Number of arguments inferred as readonly
     1 cgscc-passmgr    - Maximum CGSCCPassMgr iterations on one SCC
     5 codegen-dce      - Number of dead instructions deleted
     3 codegenprepare   - Number of blocks eliminated
    14 codegenprepare   - Number of uses of Cast expressions replaced with uses of sunken Casts
     2 codegenprepare   - Number of uses of Cmp expressions replaced with uses of sunken Cmps
     3 codegenprepare   - Number of GEPs converted to casts
     7 codegenprepare   - Number of memory instructions whose address computations were sunk
    60 dagcombine       - Number of dag nodes combined
    12 early-cse        - Number of instructions CSE'd
     2 early-cse        - Number of load instructions CSE'd
     1 functionattrs    - Number of arguments marked nocapture
     1 functionattrs    - Number of functions marked as norecurse
     2 globalopt        - Number of functions converted to fastcc
     8 globalopt        - Number of globals marked unnamed_addr
     2 globalsmodref-aa - Number of functions without address taken
     1 gvn              - Number of blocks merged
     4 gvn              - Number of instructions deleted
     3 gvn              - Number of instructions simplified
     1 gvn              - Number of loads PRE'd
     3 indvars          - Number of IV sign/zero extends eliminated
     2 indvars          - Number of loop exit tests replaced
     2 indvars          - Number of indvars widened
     2 inline           - Number of functions deleted because all callers found
     4 inline           - Number of functions inlined
     4 inline-cost      - Number of call sites analyzed
```

Improve Performance of AOSP Libraries

SARC contributions

- compiler contributions:
  - jump-threading: optimize finite state machines
  - gvn-hoisting: better scheduling, code size
  - loop rotation: to improve LICM and PRE
  - switch to jump-tables
- libcxx contributions:
  - update Android NDK libc++, make it easy to keep updated
  - 12x speedup of std::string.find() in libc++ and libstdc++ need to port perf to memmem and strstr of bionic and glibc
  - improve perf of shared_ptr
  - improve perf of string to int value parsing

Benchmarking Standard Libraries

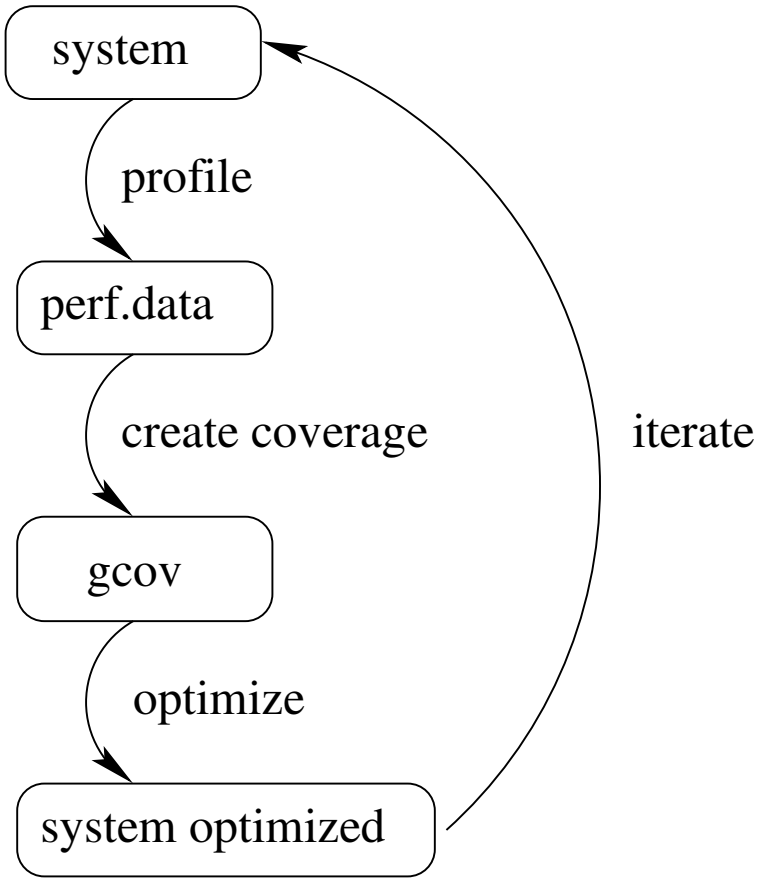
SARC contribution: std-benchmark[9]

- std-benchmark provides micro-benchmarks for functions in libc and C++ standard library
- detect room for improvement
  - compile with different compilers
  - link with different standard libraries
  - run on different machines: CPUs, architectures

[9] https://github.com/hiraditya/std-benchmark

AutoFDO: Feedback Directed Optimization

- Linux-perf extracts profiles of running systems
- little to no overhead [10]
- coverage (basic block frequencies) from dynamic profiles
- continuous profiling and tuning of optimizations



[10] Google Wide Profiling: A Continuous Profiling Infrastructure for Data Centers, IEEE Micro (2010)

AutoFDO: Example

AutoFDO: Code Optimizations

- better inlining [11], devirtualization, function instantiation
- hot/cold code placement
- register allocation, jump-threading, etc.

[11] Lightweight Feedback-Directed Cross-Module Optimization, CGO 2010

AutoFDO: More Precise Coverage

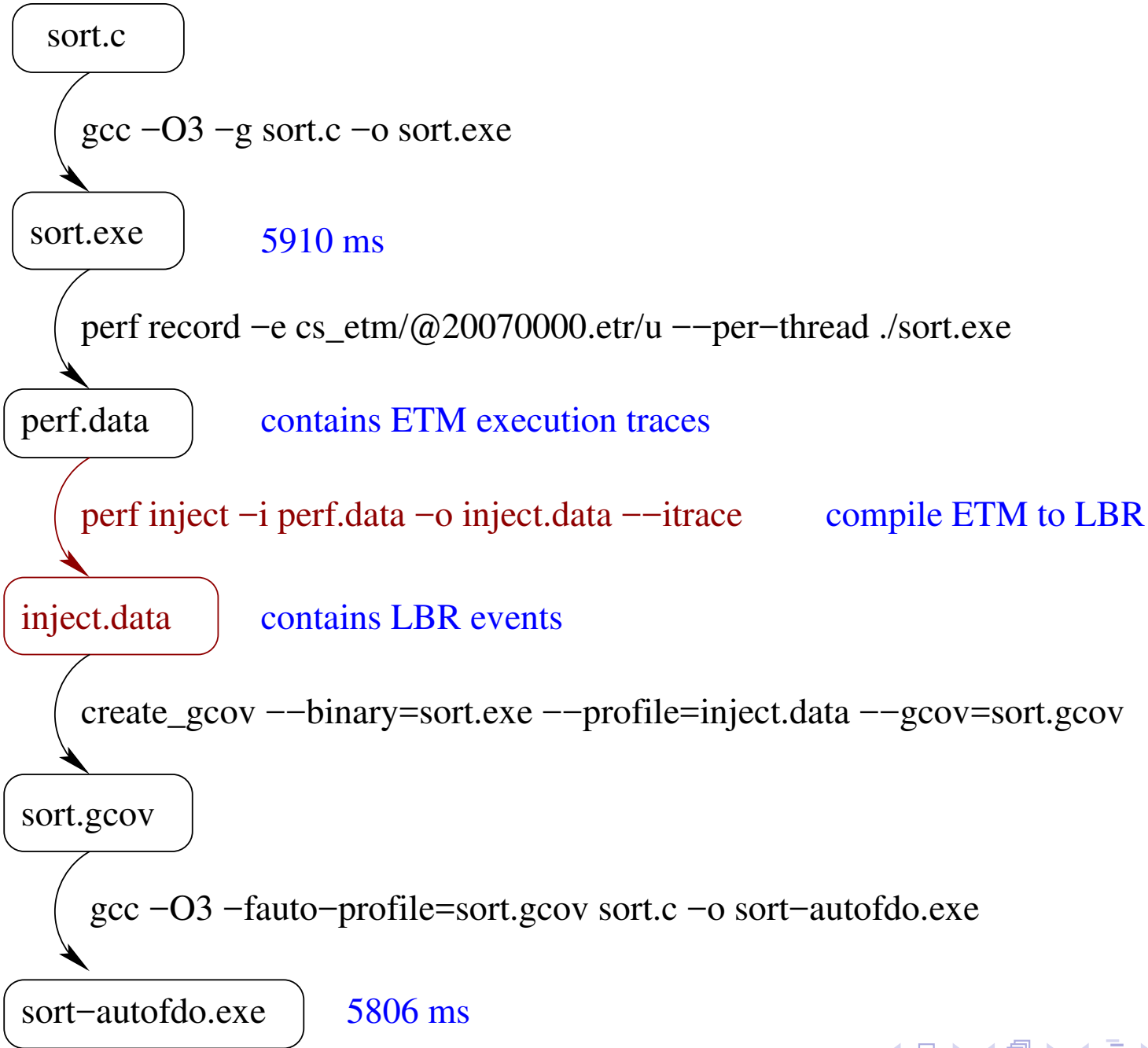
- Intel-LBR (Last Branch Record): last 16 taken branches
- provides more precise basic block execution frequency
- how do we do this on ARM?

ARM-ETM: Embedded Trace Macrocell

- ARM-ETM: records execution traces (for debug)
- dedicated circular buffer 1 to 3MB ($\sim 10^5$ branches/MB)
- no overhead
- support in Linux kernel by Mathieu Poirier (Linaro)
- next android kernel Linux-4.9 will support ARM-ETM

- **SARC contribution**: how to use ARM-ETM for AutoFDO
  - perf-inject translates execution traces to LBR events
  - patch similar to perf-inject for Intel Process Trace

AutoFDO: with ARM-ETM



From Dynamic Profiles to Power Usage

- traditionally, per app battery usage (ammeter on wire) [12]

- Linux-perf profiles provide a more accurate picture
  - profiles from the field: real world use-cases
  - merge together different profiles
  - compute code execution frequency
  - power consumption estimation per line of code [13]

[12] An Analysis of Power Consumption in a Smartphone, USENIX'10

[13] Google Wide Profiling: A Continuous Profiling Infrastructure for Data Centers, IEEE Micro (2010)

Towards More Secure Devices

- Control Flow Integrity (CFI): 2% overhead [14]
- to enable on Android: need to further reduce its cost

[14] Enforcing Forward-Edge Control-Flow Integrity in GCC&LLVM, USENIX'14

Takeaways

- outer loop is parallel $\rightarrow$ optimize the inner-most loop
- scalar optimizations to improve performance of AOSP

- AutoFDO on ARM is enabled with ETM debug facility
- Linux-perf transforms live systems into benchmarks
  - fine grain computation of power consumption
  - prioritization of performance tuning work

- Samsung phones are a galaxy in the Android cosmos