Optimizing the software stack of a cosmic proportions cluster of multi-core machines

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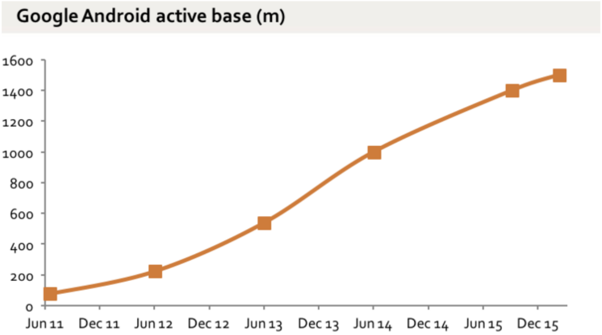
Android: a cosmic size cluster

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

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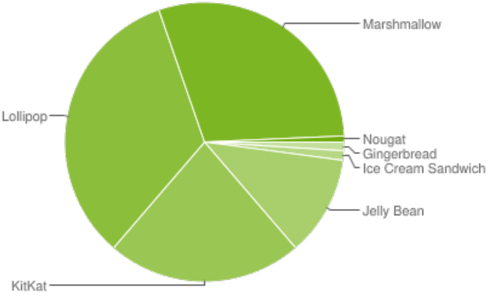
- release/updates/deprecation (5 $\sim$ 6 years)



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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.)

[6] $\$0.12/kWh$, battery $13.2Wh = 4.4V * 3000mAh$, charging every 48 hours

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Motivation:

- same code executed billions of time
- outer loop is outside the device
- 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 [6]

[6] \$0.12/kWh, battery 13.2$Wh = 4.4V * 3000mAh$, charging every 48 hours

Agenda

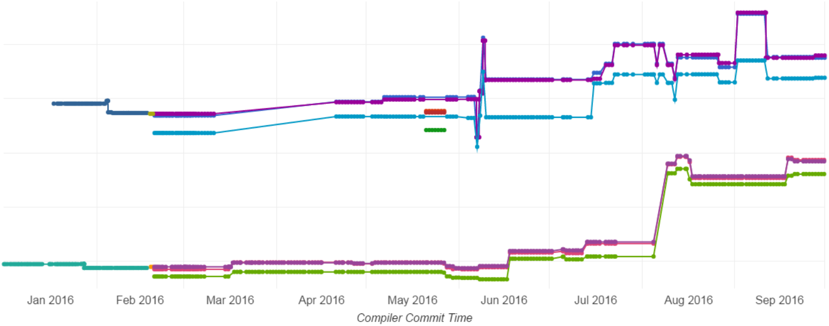
- tools for performance analysis
- improve performance of AOSP libraries
- enable continuous profiling and optimization (AutoFDO)
- enable more secure execution environments (CFI)

Performance Analysis

- benchmarks: track performance over time (compiler/libraries)
- Linux perf: profile of cycles (per function, hot-spots)
- Valgrind: number of executed instructions (branches, R/W)
- static profiles: how many uses for a function

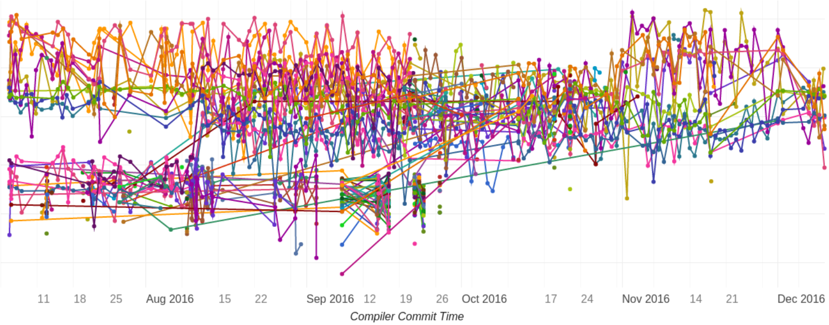
Benchmarks

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
- `valgrind --tool=callgrind`
  - execution call graph
  - visualization tool kcachegrind

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

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
```

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

Improve performance of AOSP libraries

SARC contributions

- update Android NDK libc++, make it easy to keep updated
- 20x 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 in libc++
- improve perf of string to int value parsing in libc++

Benchmarking Standard Libraries

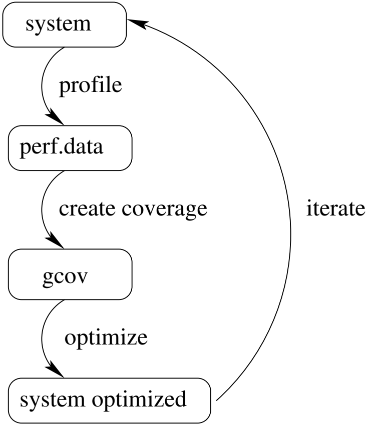
SARC contribution: std-benchmark[7]

- 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

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

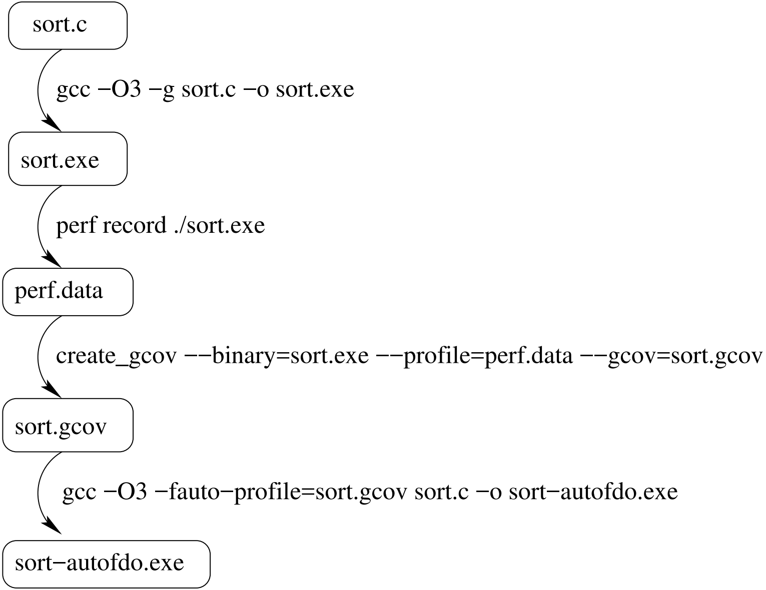
AutoFDO: Feedback Directed Optimization

- Linux-perf extracts profiles of running systems
- little to no overhead [8]
- coverage (basic block frequencies) from dynamic profiles
- continuous profiling and tuning of optimizations



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

AutoFDO: Example



AutoFDO: Code Optimizations

- better inlining [9], devirtualization, function instantiation
- hot/cold code placement
- register allocation, jump-threading, etc.

[9] 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

sort.c

gcc −O3 −g sort.c −o sort.exe

sort.exe

perf record −e cs_etm/@20070000.etr/u −−per−thread ./sort.exe

perf.data

contains ETM execution traces

perf inject −i perf.data −o inject.data −−itrace

compile ETM to LBR

inject.data

contains LBR events

create_gcov −−binary=sort.exe −−profile=inject.data −−gcov=sort.gcov

sort.gcov

gcc −O3 −fauto−profile=sort.gcov sort.c −o sort−autofdo.exe

sort−autofdo.exe

From Dynamic Profiles to Power Usage

- traditionally, per app battery usage (ammeter on wire) [10]
- more accurate picture with Linux-perf profiles:
  - profiles from the field: real world use-cases
  - merge together different profiles
  - compute code execution frequency
  - power consumption estimation per line of code

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

Towards more secure devices

- Control Flow Integrity (CFI): 2% overhead [11]
- to enable on Android: need to further reduce its cost

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