

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

Sebastian Pop

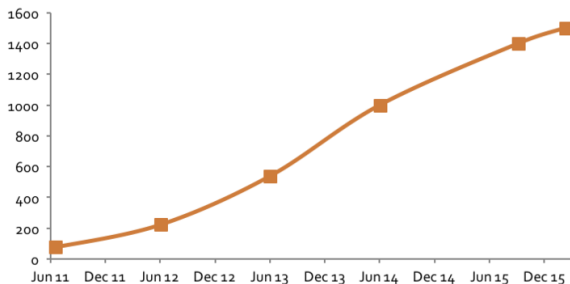
SARC: Samsung Austin R&D Center

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Android: a Cosmic Sized Cluster

- ▶ top500: 10M cores / 15.3MW¹ / US\$273 million²
- ▶ Android devices: $\sim 6B$ cores³ / $\sim 300MW$ ⁴ / $\sim US\$0$

Google Android active base (m)



[Source: Google, a16z]

¹<https://www.top500.org/lists/2016/11>

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

³4 cores / device

⁴battery 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

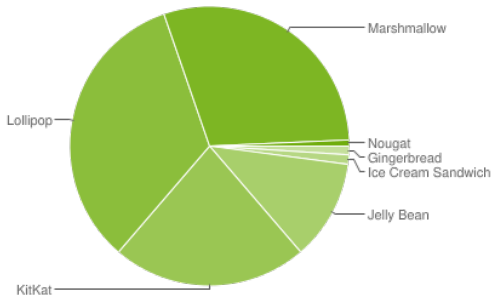
ansic	22 MLoC	39%
cpp	13 MLoC	23%
java	10 MLoC	17%
- ▶ ~ 80% execution cycles in C/C++, ~ 20% in Java

⁵Data collected during a 7-day period ending on January 9, 2017.

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- ▶ release/updates/deprecation (5 ~ 6 years)



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

Why Optimizing the Performance of Android?

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Motivation:

- ▶ same code executed billions of time
- ▶ outer loop is outside the device →
 - ▶ 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 ⁶



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

Agenda

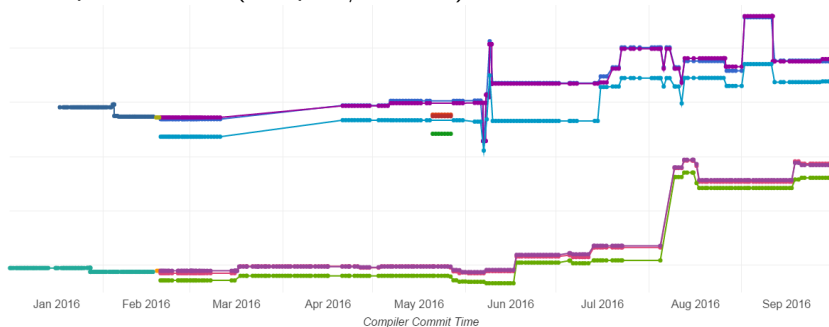
- ▶ tools for performance analysis
- ▶ improve performance of AOSP libraries
- ▶ enable continuous profiling and optimization (AutoFDO)
- ▶ enable more secure execution environments (CFI)

Performance Analysis

- ▶ benchmarks
- ▶ Linux perf
- ▶ Valgrind
- ▶ static profiles

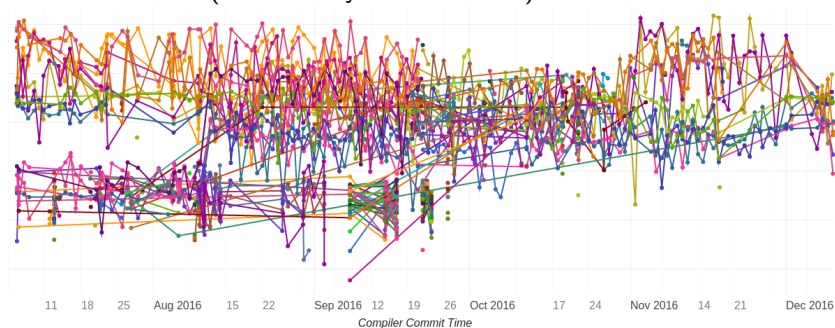
Benchmarks

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 ⁷
- ▶ `valgrind --tool=callgrind`
 - ▶ execution call graph
 - ▶ visualization tool kcachegrind

⁷https://github.com/bmrzycki/cg_difftext

Valgrind: Example – SQLite

```
$ valgrind --tool=cachegrind ./sqlite_llvm <test.sql >/dev/null  
[...]
```

	Ir	IImr	ILmr	Dr	DImr	DLmr	Dw	DImw	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	IImr	ILmr	Dr	DImr	DLmr	Dw	DImw	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:memcpy	
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:btreeParseCellIPtr	
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/ptthread_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/ptthread_mutex_unlock.c:pthread_mutex_unlock	
8,916,165	82,925	47	2,092,310	0	0	1,933,573	1,583	3	src/sqlite3.c:memjournalWrite	
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:memset	
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
- ▶ -mlvm -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 cgscpp-passmgr  - Maximum CGSCPPassMgr 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 globalmodref-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

- ▶ 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` in libc++
- ▶ improve perf of string to int value parsing in libc++
- ▶ 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

Benchmarking Standard Libraries

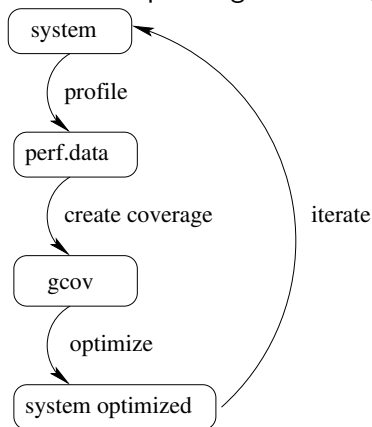
SARC contribution: std-benchmark⁸

- ▶ 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

⁸<https://github.com/hiraditya/std-benchmark>

AutoFDO: Feedback Directed Optimization

- ▶ Linux-perf extracts profiles of running systems
- ▶ little to no overhead ⁹
- ▶ coverage (basic block frequencies) from dynamic profiles
- ▶ continuous profiling and tuning of optimizations



⁹Google Wide Profiling: A Continuous Profiling Infrastructure for Data Centers, IEEE Micro (2010)

AutoFDO: Example



AutoFDO: Code Optimizations

- ▶ better inlining¹⁰, devirtualization, function instantiation
- ▶ hot/cold code placement
- ▶ register allocation, jump-threading, etc.

¹⁰Lightweight Feedback-Directed Cross-Module Optimization, CGO 2010

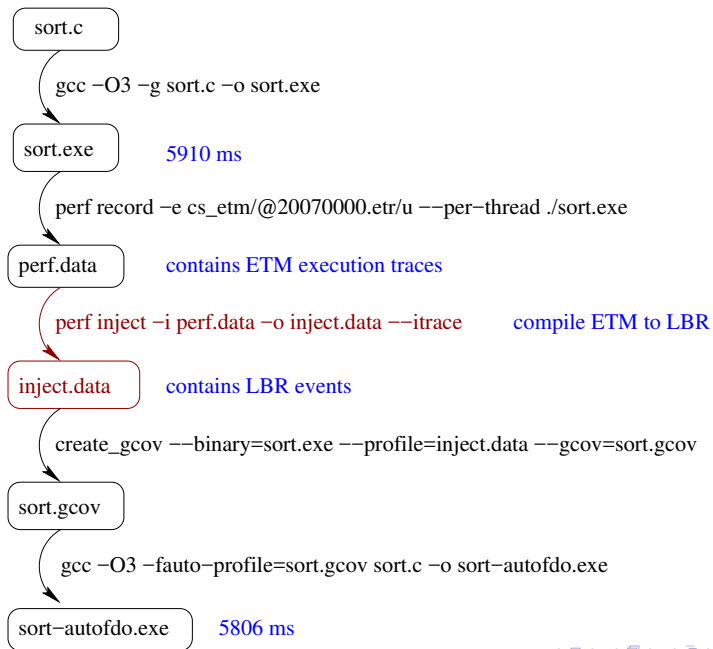
AutoFDO: More Precise Coverage

- ▶ 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) ¹¹
- ▶ 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

¹¹An Analysis of Power Consumption in a Smartphone, USENIX'10

Towards More Secure Devices

- ▶ Control Flow Integrity (CFI): 2% overhead ¹²
- ▶ to enable on Android: need to further reduce its cost

¹²Enforcing Forward-Edge Control-Flow Integrity in GCC&LLVM, USENIX'14