Optimizing large applications

Honza Hubička
SuSE ČR s.r.o
Martin Liška
Charles University

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Hi,
Just wanted to give a heads up on what might be the biggest compiler-upgrade-related performance difference we've seen at Mozilla.

We switched gcc4.3 for gcc4.5 and our automated benchmarking infrastructure reported 4-19% slowdown on most of our performance metrics on 32 and 64bit Linux.

... 

Most of the code is compiled with -fPIC -fno-rtti -fno-exceptions -Os -freorder-blocks -fomit-frame-pointer.

Taras Glek (2010)
First look at firefox situation

Why they use so old GCC for release builds? It builds just fine with trunk GCC.

...why they build with -Os and complain about runtime?

This beast is much bigger than I expected... why all the performance critical functionality is in a library libxul rather than main firefox binary?

...why libxul contains private copies of libffi, gtk, cairo, you name it...
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- why all the performance critical functionality is in a library `libxul` rather than main firefox binary?
- why `libxul` contains private copies of `libffi`, `gtk`, `cairo`, you name it, . . .
- `−O2` the default optimization level supposed to do wise code size vs performance tradeoffs.

- `−O3` optimize performance as much as possible! . . . shoot yourself into leg if program is too big

  automatic inlining, function specialization, autovectorization, loop unswitching, memset/memcpy discovery, . . .

- `−Os` reduce size as much as possible

  Inline and specialize only when code shrinks

  Instruction selection (push, pop, rep movsb, rep stosb, mult / idiv by constant rather than sequence of arithmetics, . . .

  No code expanding optimizations (unrolling, vectorizing)

Over time

- `−O3` code gets bigger and slightly faster,
- `−Os` code gets much slower and (sometimes) slightly smaller.
Optimizations levels at a glance

- **-O2**: the default optimization level supposed to do wise code size vs performance tradeoffs.
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Over time **-O3** code gets bigger and slightly faster, **-Os** code gets much slower and (sometimes) slightly smaller.
–Os was designed with low level programming in mind. It happens when:

1. When static function is inlined few enough times so whole compile units shrinks after it is fully inlined.
2. When caller is known to shrink after inlining.
Fixing \texttt{-Os} for firefox.

\texttt{-Os} was designed with low level programming in mind. It happens when:

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C++ inline functions are usually not static/in anonymous namespace. COMDAT sections merged at linktime.
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C++ inline functions are usually not static/in anonymous namespace. COMDAT sections merged at linktime.

- Rule 1 never applies here.

-param comdat-sharing-probability=20% specify chance that unification at linktime happens.
Fixing -O0 for firefox.

-O0 was designed with low level programming in mind. It happens when:

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C++ inline functions are usually not static/in anonymous namespace. COMDAT sections merged at linktime.

- Rule 1 never applies here.
  -param comdat-sharing-probability=20% specify chance that unification at linktime happens.

- Rule 2 is too weak. GCC inliner can anticipate just fraction of optimizations. I made inliner to gamble.
Firefox and optimizations levels

Half a year later...
Half a year later . . .

“Hey I fixed the \-O_s problems. It was a piece of a cake.”
Half a year later...

“Hey I fixed the \(-O_s\) problems. It was a piece of a cake.”

“Oh cool. But we use \(-O_3\) now…”
Half a year later . . .

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...we solved the startup time issues.”
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“Uh, why you don’t use \texttt{-O2}?“

...we solved the startup time issues.”

“hmm, startup time issues?”
Firefox startup

File Offset 21M
15% relocations
46% static initializers
6% misc runtime linker
21M0M

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Startup overview

- Kernel memory maps the binary and starts dynamic linker
  - Page demand loading loads only pages touched by the app
  - Prefetch heuristic attempts to reduce random seeking
  - Based on ELF header kernel dispatch to the dynamic linker

Dynamic linker
- Mmaps shared libraries
- Process relocations except PLT and fixes memory image
- Executes actual program

Program's runtime
- Execute all static constructors in priority order.
  - If priorities match, constructors are executed backwards so libraries are constructed first
- Execute main()
- The program does something hopefully useful until it crashes.
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  - Execute all static constructors in priority order.
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- program does something hopefully useful until it crashes.
ELF answer to shared libraries (1995—1999)

`.a.out` shared libraries was hell to maintain
- Required central authority for address space distribution
- Required hand crafted entry points with indexes

Symbol interposition allows rewriting of given symbol

LD_PRELOAD

Versioning allows better backward compatibility

Some performance features (visibilities) are provided
a.out shared libraries was hell to maintain

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ELF introduced shared libraries that are very flexible

- Linking is done based on symbol name at runtime by dynamic linker
- shared libraries are flexible first
  - Symbol interposition allows rewriting of given symbol
    LDL_PRELOAD
  - Versioning allows better backward compatibility
- Some performance features (visibilities) are provided
PIC programming model tells compiler to
- Use IP relative addressing whenever possible.

Assume that most symbols can be overwritten at runtime. (tricky to change for exported symbols)

Decades old assumptions:
- Static variable initializers rarely take address of symbol.
- It is not too common to take address of function or static variable in code (only for `qsort`).
- Hot parts of programs are not in shared library.
PIC programming model tells compiler to
- Use IP relative addressing whenever possible.
- Instead of calling external function directly, call to IP relative PLT entry. This triggers linking only first time function is called.

Instead of referring to variable directly use GOT (Global Offset Table) to concentrate relocations to single place. Assume that most symbols can be overwritten at runtime. (tricky to change for exported symbols)

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libxul startup

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Libreoffice startup

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Libreoffice startup, read-ahead enabled

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libxul startup, startup problem solved

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Optimizing large applications
During login procedure start process `kdeinit` containing all the shared libraries.

Instead of executing an KDE application, fork `kdeinit` and `dlopen`. 
Prelink (2004)

Tool developed by Jakub Jelínek

- After installation whole distro is walked, binaries are analyzed and conflict graph of shared libraries is built.
- Shared libraries get assigned fixed addresses in the address space.
- Binaries are prelinked - i.e. linked with assumption that libraries are at given positions.
- Dynamic linking is performed only when something changed from prelinking time. (fallback mode)
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Prelink offers great speedups, but has number of issues

- The prelinking modifies all binaries on disk making it difficult to detect changes, increasing fragmentation
- The fallback mode is triggered often (by `dlopen`, ...)
C++ programs spent a lot of CPU time in dynamic linking comparing symbol names. It grows with \( \text{num-libraries} \times \text{avg-symbol-length} \).
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- `.gnu.hash` section
- 2-bit Bloom filter used for fast lookup if symbol is defined at all in a given DSO.
- Stronger hash function for actual lookup
- Optimized `strcmp`

Overall GNU hash reduce about 15% of firefox dynamic linking time. (by `LD_DEBUG=statistic`)
libxul startup, elfhack applied

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Optimizing large applications
ELFhack = relocations on diet (2010)

Hack introduced by Mike Hommey

- 20% of Firefox libxul image are relocations
- 208k relocations out of 239k relocations are IP relative.
- ELF relocations are not terribly size optimized
  - REL relocations on x86 take 8 bytes
  - RELA relocation on x86-64 take 24 bytes

Elfhack compress the relocations
Elfhack removes IP relative ELF relocations and store them in compact custom format. It handles well sequences of IP relative relocations in vtables.

After ELF linking, Elfhack linking completes the process.
Elfhack is general tool but not compatible with -z relro security feature.

7.5MB of relocations → 0.3MB.
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  - ELFhack is general tool but not compatible with -z retro security feature.

- 7.5MB of relocations $\rightarrow$ 0.3MB.
Current Firefox’ solution to startup time problems

- Firefox startup touches almost every page in the binary
- Hacking dynamic linker to do `mmap` makes kernel to load it sequentially
GIMP startup

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Optimizing large applications
Split text section into:
- Hot subsection
- Normal subsection
- Unlikely executed subsection
- Startup only subsection (new in 2010), ordering solved by `.initarray`
- Exit only subsection (new in 2010)

Split data into
- readonly data
- data w/o relocations in it
- data with IP relative relocations
- readonly data with IP relative relocations
- data with all kinds of relocations
- readonly data with all kinds of relocations
The catch

Warning: no gold support until the next release of binutils
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Hot/cold code decisions are difficult for the compiler.

\(-O2 \iff\) “everything may be hot unless you know it is not”
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\[ \texttt{-O2} \iff \text{"everything may be hot unless you know it is not"} \]

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- Feedback directed optimization is feasible even for GUI apps.
  - It is used by firefox
  - GUI code is usually not the bottleneck, train the rest
  - Even not too representative data often works in practice
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- \texttt{cold} and \texttt{hot} function attributes (2007)
  - Paths leading to calls to \texttt{cold} function are cold
  - Functions called only by cold functions are cold.
  - No use of \texttt{cold attribute in /usr/include} found :(
Feedback directed reordering (2013)

- Measure first time of function execution
- Order functions increasingly in time in the resulting binary
Feedback directed reordering (2013)

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- Initial experiments by Taras Glek with hacked valgrind

Currently needs linktime optimization. For non-LTO use needs linker support that is being discussed.
Measure first time of function execution
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Implemented to GCC FDO by Martin Liška as his thesis and SoC project (will be merged into GCC 4.9 soon)
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GIMP startup with subsections

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GIMP startup with reordering

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Inkscape with reordering

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Inkscape with function splitting

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Optimizing large applications
Ordering by invocation time is cool for startup
For main execution it is good to minimize call distance
  - Reverse postorder is a good first try, but too simplistic
  - Clustering program by edges ordered by frequency ignore indirect calls. Experiments from 2010 did not show any benefits over RPO.
Profile data needs to be complete (work currently in progress)
  - Better support for COMDAT functions
  - Crossmodule indirect call profiling
  - Profiling of thunks

We plan to experiment with algorithm starting from invocation time order performing local optimizations to minimize hot calls
We need non-profile based code placement algorithm

- Main problem seems to be lack on information on indirect call
  - Polymorphic call target analysis implemented last week
  - Normal indirect call are in minority, can be pruned by types and points-to
- Maybe we need global profile propagation for educated guesses on what is hot call edge.
- We plan to honor original program order as a starting point.
  - Is it better than reverse postorder or random order?
Link time optimization (LTO) extends the scope of interprocedural analysis from single source file to whole program visible at the link time.
Link time optimization (LTO) extends the scope of interprocedural analysis from single source file to whole program visible at the link time

- Implemented by calling back to the optimizer backend from the linker.
- Development started in 2005, merged to mainline in 2009.
- First released in GCC 4.5.
What can be built

- GCC itself (GCC 4.5+)
- SPEC2k6 benchmarks (GCC 4.5+)
- Firefox (GCC 4.7+)
- Kernel (thanks to Andi Kleen, GCC 4.8+)
- Chrome and Libreoffice (thanks to Martin Liška GCC 4.9+)

Minor patches usually needed for symbols used from ASM statements. Major hacks needed for kernel.
Memory/CPU usage during Firefox build

CPU utilization

memory usage

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After type merging rewrite by Richard Biener

![Graph of CPU utilization and memory usage over time](image)

**CPU utilization**

- %
- 0 100 200 300 400 500
- time (s)
- 0 2 4 6 8 10 12 14 16

**Memory usage**

- RAM (in GB)
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After early virtual method removal

CPU utilization

memory usage

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With better partitioning and parallel streaming

CPU utilization

memory usage

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Full build — no-LTO, -O2

CPU utilization

memory usage

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Full build — LTO, 6% slower

CPU utilization

memory usage

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LTO performance and code size

SPEC2006 relative to -O2;

PGO = Profile Guided Optimization
-fprofile-generate/-fprofile-use

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<td>-O3+LTO</td>
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UG5 = -O3, -flto -param inline-unit-growth=5%

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LTO performance and code size

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<td>1.51%</td>
<td>1.23%</td>
</tr>
<tr>
<td>-O3+LTO</td>
<td>3.27%</td>
<td>-1.65%</td>
<td>9.82%</td>
<td>5.62%</td>
</tr>
<tr>
<td>-O3+PGO</td>
<td>7.43%</td>
<td>11.75%</td>
<td>8.35%</td>
<td>8.21%</td>
</tr>
<tr>
<td>-O3+PGO+LTO</td>
<td>-4.68%</td>
<td>-11.39%</td>
<td>12.41%</td>
<td>12.16%</td>
</tr>
<tr>
<td>UG5</td>
<td>-1.23%</td>
<td>-9.67%</td>
<td>9.29%</td>
<td>3.77%</td>
</tr>
</tbody>
</table>

| UG5 = -O3, -flto -param inline-unit-growth=5% |

---

J. Hubička Optimizing large applications
SpecFP2k6 non-LTO rates (-O2 +3%; -Ofast, +14%)
LTO only optimization

What matters:
- Aggressive unreachable code removal
  (15%–20% code size savings)
- Cross-module inlining
  (almost all spec2k6 speedups come from it)
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  (over 20% fewer pages read at gimp startup, currently works well only with profile)
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  (important for programs with many polymorphic calls)
- Constructor/destructor merging
  (C++ only, measurable at firefox startup time)
- Identical function merging
  (Work in progress by Martin Liška, ICF in gold)
LTO only optimization

What is on the way

- Reducing program growth to 5% for larger LTO builds (5-20% code size savings)
- Getting rid of external relocations when C++ allows it
  Seems to help to libreoffice. Do we want
  \texttt{-fno-semantic-interposition} flag?
- Static function reordering
- Type inheritance analysis, devirtualization, speculative devirtualization
- \texttt{-fno-fat-lto-objects} by default
Command line options behave in unexpected ways
be sure to LTO only stuff that needs one global
optimization setting. Do not LTO modules that needs
specific flags (like `-march`, `-ffast-math` or so)

There is no way to define symbols from asm statements in
LTO units
do not LTO these as workaround

Debug info quality is not at match with non-LTO path
(it gets better though)
### Compared to 2010

<table>
<thead>
<tr>
<th></th>
<th>compile</th>
<th>serial link</th>
<th>parallel link</th>
<th>LTO cost</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>9m</td>
<td>4m 27s; 4GB</td>
<td>1m 03s</td>
<td>70%</td>
<td>21m</td>
</tr>
<tr>
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<td>35m</td>
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<td>6%</td>
<td>47m</td>
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Thank you!

Questions?