IISWC-2006 Tutorial

Building Workload Characterization Tools with Valgrind

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This tutorial

1. Introduction to Valgrind
2. Example profiling tools
3. Building a new Valgrind tool
4. More advanced tools

(end of tutorial overview)

1. Introduction to Valgrind

Robert Walsh

This talk

- What is Valgrind?
- Who uses it?
- How it works

What is Valgrind?

Valgrind is…

- A framework
  - For building program analysis tools
  - E.g. profilers, visualizers, checkers
- A software package, containing:
  - Framework core
  - Several tools: memory checker, cache profiler, call graph profiler, heap profiler
- Memcheck, the most widely used tool, is often synonymous with “Valgrind”

What kind of analysis? (1/2)

- Categorization 1: when does analysis occur?
  - Before run-time: static analysis
    - Simple preliminaries: parsing
    - Complex analysis: e.g. abstract interpretation
    - Imprecise, but can be sound: sees all execution paths
  - At run-time: dynamic analysis
    - Complex preliminaries: instrumentation
    - Simpler analysis: "Perfect light of run-time"
    - Powerful, but unsound: sees one execution path
- Valgrind performs dynamic analysis

What kind of analysis? (2/2)

- Categorization 2: what code is analyzed?
  - Source code: source-level analysis
    - Language-specific
    - Requires source code
    - High-level information: e.g. variables, statements
  - Machine code: binary analysis
    - Language-independent (can be multi-language)
    - No source code (but debug info helps)
    - Lower-level information: e.g. registers, instructions
- Valgrind performs binary analysis

Dynamic binary analysis

	Static	Dynamic
Source	Static source-level analysis	Dynamic source-level analysis
Binary	Static binary analysis	**Dynamic binary analysis**

- Valgrind: dynamic binary analysis (DBA)
  - Analysis of machine code at run-time
  - *Instrument* original code with *analysis code*
  - Track some extra information: *metadata*
  - Do some extra I/O, but don't disturb execution otherwise

What kind of instrumentation?

- Categorization: When does binary instrumentation occur?
  - Before run-time: static binary instrumentation (SBI)
    - A.k.a. binary rewriting
  - At run-time: dynamic binary instrumentation (DBI)
- Valgrind uses DBI. Compared to SBI:
  - No preparation (e.g. recompilation) required
  - All user-mode code instrumented
    - Dynamically loaded libraries
    - Dynamically generated code
    - No code/data identification difficulties
  - Instrumentation cost incurred at run-time
- A good DBI framework mitigates the run-time cost and makes tool-writing much easier

An aside

- Similar things to DBA and DBI:
  - 1. Dynamic binary optimisation
    - Rewrite binary on-the-fly for speed-ups
    - E.g. Dynamo
  - 2. Dynamic binary translation
    - Run binary for platform X on platform Y
  - 3. Semantics-affecting tools
    - E.g. sandboxing, fault injection
- Not talking about these
  - Valgrind tools can do (3), but usually don’t

Similar systems

- DBI frameworks:
  - Pin, DynamoRIO, DIOTA, DynInst, etc.
  - Lots of overlap
  - Each system supports different platforms
- Purify, Chaperon (part of Insure++)
  - Memcheck (a memory-checking tool) is similar
- Valgrind:
  - GPL
  - Widely used, robust
  - Slower for simple tools
  - Designed for heavyweight tools, especially shadow value tools (more in talk 4)

Who uses Valgrind?

Valgrind users

- Developers
  - C (43%), C++ (49%), Fortran, Ada, Java
  - Firefox, OpenOffice, KDE, GNOME, libstdc++, PHP, Perl, Python, MySQL, Samba, RenderMan, NASA, CERN, Unreal Tournament, parts of the Linux kernel
  - Biggest program we know of: 25 MLOC
  - Memcheck: 80% of usage, other tools still widespread
- Researchers
  - Cambridge, MIT, CMU, UT, UNM, ANU, etc.
  - For building new kinds of analysis tools
  - For experimental evaluation of programs (Cachegrind)
- Website receives >1000 unique visitors per day

Availability

- Free software (GPL)
- Standard Linux package
- Platforms:
  - Valgrind 3.2.1: x86/Linux, AMD64/Linux, PPC{32,64}/Linux
  - In repository: PPC{32,64}/AIX
  - Under development: PPC32/Darwin, x86/Darwin, x86/FreeBSD, others
- www.valgrind.org

How does Valgrind work?

Basic architecture

- Valgrind core + tool plug-in = Valgrind tool
- Core:
  - Executes the *client program* under its control
  - Provides services to aid tool-writing
    - E.g. error recording, debug info reading
- Tool plug-ins:
  - Main job: instrument code blocks passed by the core
- Lines of code (mostly C, a little asm in the core):
  - Core: 173,000
  - Call graph profiler: 11,800
  - Cache profiler: 2,400
  - Heap profiler: 1,700

Running a Valgrind tool (1/2)

```
[nevermore:~] date
Sat Oct 14 10:28:03 EST 2006
[nevermore:~] valgrind --tool=cachegrind date
==17789== Cachegrind, an I1/D1/L2 cache profiler.
==17789== Copyright (C) 2002-2006, and GNU GPL'd, by Nicholas Nethercote et al.
==17789== Using LibVEX rev 1601, a library for dynamic binary translation.
==17789== Copyright (C) 2004-2006, and GNU GPL'd, by OpenWorks LLP.
==17789== Using valgrind-3.2.1, a dynamic binary instrumentation framework.
==17789== Copyright (C) 2000-2006, and GNU GPL'd, by Julian Seward et al.
==17789== For more details, rerun with: -v
==17789==
Sat Oct 14 10:28:12 EST 2006
==17789==
==17789== I   refs:      395,633
==17789== I1  misses:      1,488
==17789== L2i misses:      1,404
==17789== I1  miss rate:    0.37%
==17789== L2i miss rate:    0.35%
==17789==
==17789== D   refs:      191,453  (139,922 rd + 51,531 wr)
==17789== D1  misses:      3,012  (  2,467 rd +    545 wr)
==17789== L2d misses:      1,980  (  1,517 rd +    463 wr)
==17789== D1  miss rate:     1.5% (    1.7%   +    1.0%  )
==17789== L2d miss rate:     1.0% (    1.0%   +    0.8%  )
==17789==
==17789== L2 refs:         4,500  (  3,955 rd +    545 wr)
==17789== L2 misses:       3,384  (  2,921 rd +    463 wr)
==17789== L2 miss rate:      0.5% (    0.5%   +    0.8%  )
```

Running a Valgrind tool (2/2)

- Tool output goes to stderr, file, fd or socket
- Program behaviour otherwise unchanged…
- …except much slower than normal
  - No instrumentation: 4-10x
  - Memcheck: 10-60x
  - Cachegrind: 20-100x
- For most tools, slow-down mostly due to analysis code

Starting up

- Valgrind loads the core, chosen tool and client program into a single process
- Lots of resource conflicts to handle, via:
  - Partitioning: address space, fds
  - Time-multiplexing: registers
  - Sharing: pid, current working directory, etc.
- Starting up is difficult to do robustly
  - Currently on our 3rd core/tool structuring and start-up mechanism!

Dynamic binary recompilation

- JIT translation of small code blocks
  - Often basic blocks, but can contain jumps
  - Typically 5-30 instructions
- Before a code block is executed for the first time:
  - Core: machine code → (architecture neutral) IR
  - Tool: IR → instrumented IR
  - Core: instrumented IR → instrumented machine code
  - Core: caches and links generated translations
- No original code is run
- Valgrind controls every instruction
  - Client is none the wiser

Complications

- System calls
  - Valgrind does not trace into the kernel
  - Some are checked to avoid core/tool conflicts
  - Blocking system calls require extra care
- Signals
  - Valgrind intercepts handler registration and delivery
  - Required to avoid losing control
- Threads
  - Valgrind serializes execution (one thread at a time)
  - Avoids subtle data races in tools
  - Requires reconsideration due to architecture trends

Function wrapping/replacement

- Function replacement
  - Can replace arbitrary functions
  - Replacement runs as if native (i.e. it is instrumented)
- Function wrapping
  - Replacement functions can call the function they replaced
  - This allows function wrapping
  - Wrappers can observe function arguments
- System call wrapping
  - Similar functionality to function wrapping
  - But separate mechanism

Client requests

- Trap-door mechanism
  - An unusual no-op instruction sequence
  - Under Valgrind, it transfers control to core/tool
  - Client can pass queries and messages to the core/tool
  - Allow arguments and a return value
  - Augments tool's standard instrumentation
- Easy to put in source code via macros
  - Tools only need to include a header file to use them
  - They do nothing when running natively
  - Tool-specific client requests ignored by other Valgrind tools
- Example:
  - Memcheck instruments malloc and free
  - Custom allocators can be marked with client requests that say "a heap block was just allocated/freed"
  - A little extra user effort helps Memcheck give better results

Self-modifying code

- Without care, self-modifying code won't run correctly
  - Dynamically generated code is fine if it doesn't change
  - But if changed, the old translations will be executed
- An automatic mechanism:
  - Hash of original code checked before each translation is executed
  - Expensive, by default on only for code on the stack
  - E.g. handles GCC trampolines for nested functions (esp. for Ada)
- A manual mechanism:
  - A built-in client request: "discard existing translations for address range A..B"
  - Useful for dynamic code generators, e.g. JIT compilers

Forests and trees

- Valgrind is a framework for building DBA tools
- Interesting in and of itself
  - But it is a means to an end
- The tools themselves are the interesting part
  - Actually, it is what the tools can tell you about programs that is really the interesting part
- Next three talks cover:
  - Existing profiling tools
  - How to write new tools
  - Some ideas for interesting new tools

(end of talk 1)

2. Example profiling tools

Jeremy Fitzhardinge

This talk

- Three existing profiling tools
  - Cache profiler
  - Call graph profiler
  - Heap profiler

Cachegrind: a cache profiler

Cachegrind

- Cache behaviour is crucial
  - L1 misses: ~10 cycles
  - L2 misses: ~200 cycles
- But difficult to predict
- Cachegrind gives three outputs:
  - Total hit/miss counts and ratios (I1, D1, L2)
  - Per-function hit/miss counts (sorted from most to least)
  - Per-line hit/miss counts (source code annotations)
- Source code annotations are the most useful
  - Most fine-grained data
  - Data that programmers can act on to speed up their programs

Sample output

```
--------------------------------------------------------------------------------
        Ir I1mr I2mr        Dr D1mr D2mr        Dw      D1mw      D2mw
--------------------------------------------------------------------------------
14,789,396  547  544 6,329,792  751  689 2,111,757 1,113,292 1,094,855  PROGRAM TOTALS

--------------------------------------------------------------------------------
        Ir I1mr I2mr        Dr D1mr D2mr        Dw      D1mw      D2mw  file:function
--------------------------------------------------------------------------------
14,688,273    1    1 6,294,531    0    0 2,098,178 1,113,088 1,094,656  example.c:main

--------------------------------------------------------------------------------
-- Auto-annotated source: example.c
--------------------------------------------------------------------------------
       Ir I1mr I2mr        Dr D1mr D2mr        Dw      D1mw      D2mw

        .    .    .         .    .    .         .         .         .  int main(void)
       10    0    0         0    0    0         1         0         0  {
        .    .    .         .    .    .         .         .         .     int i, j, a[1024][1024];
        .    .    .         .    .    .         .         .         .
    4,100    1    1     2,049    0    0         1         0         0     for (i = 0; i < 1024; i++) {
4,198,400    0    0 2,098,176    0    0     1,024         0         0        for (j = 0; j < 1024; j++) {
5,242,880    0    0 2,097,152    0    0 1,048,576    65,536    56,320           a[i][j] = 0;   // fast
5,242,880    0    0 2,097,152    0    0 1,048,576 1,047,552 1,038,336           a[j][i] = 0;   // slow
        .    .    .         .    .    .         .         .         .        }
        .    .    .         .    .    .         .         .         .     }
        1    0    0         0    0    0         0         0         0     return 0;
        2    0    0         2    0    0         0         0         0  }
```

How Cachegrind works

- Each instruction is instrumented
  - Call to a C cache simulation function
  - Different functions for loads, stores, modifies
  - Some combining of C calls for efficiency
- Each source code line gets a *cost centre*
  - Holds counters: accesses, hits and misses
  - Uses debug info to map each instruction to a cost centre
- Online simulation (i.e. no trace gathering)
- Cost centres dumped to file at end
  - Simple but compact text format
  - Post-processing script produces previous slide's output

Cache simulation

- Approximates an AMD Athlon hierarchy
  - I1, D1, inclusive L2
  - Write-allocate
  - LRU replacement
- Each cache is command-line configurable:
  - Cache size
  - Line size
  - Associativity
- On x86/AMD64 can use CPUID to auto-detect these parameters
- Simulation can be replaced easily

Inaccuracies

- Imperfect address trace
  - No kernel code
  - Other processes ignored (arguably good)
  - Conversion to Valgrind’s IR changes a very small number of loads/stores
- Incorrect addresses
  - Virtual addresses
  - Memory layout and thread scheduling is different under Cachegrind compared to native
- Prefetches and cache-bypassing are ignored
  - Difficult to handle well without detailed microarchitectural simulation
- Still useful for general insights

How is it used?

- Characterization:
  - Program A vs. program B
  - Cache hierarcy A vs. cache hierarchy B
- Optimisation:
  - Identifies cache-unfriendly code
  - Fixing such code requires non-trivial insight
    - But easier (i.e. not impossible!) than fixing without this data
- Evaluation of optimisations:
  - Program A vs. optimised program A

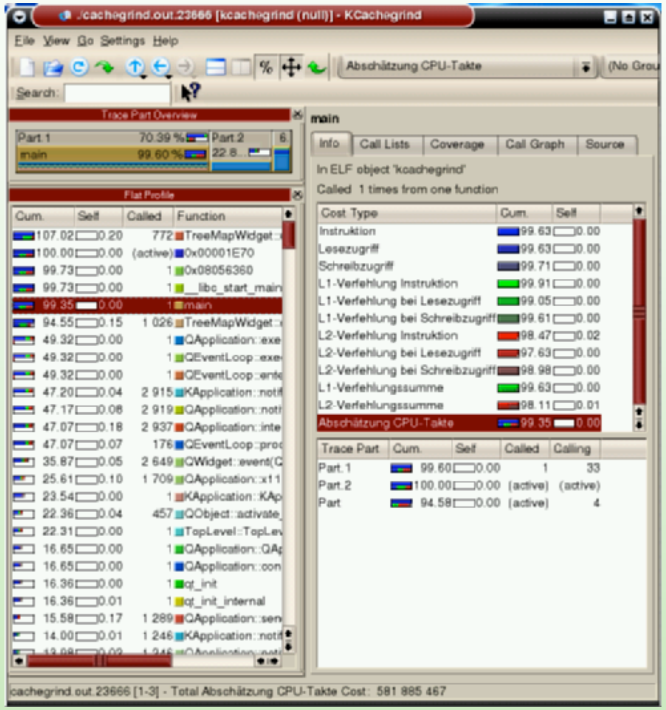
Cachegrind summary

- Cachegrind is a cache simulator
- Gives total, per-function and per-line hit/miss counts
- Simulation is imperfect, but still useful
- Used for characterization, optimisation and evaluation

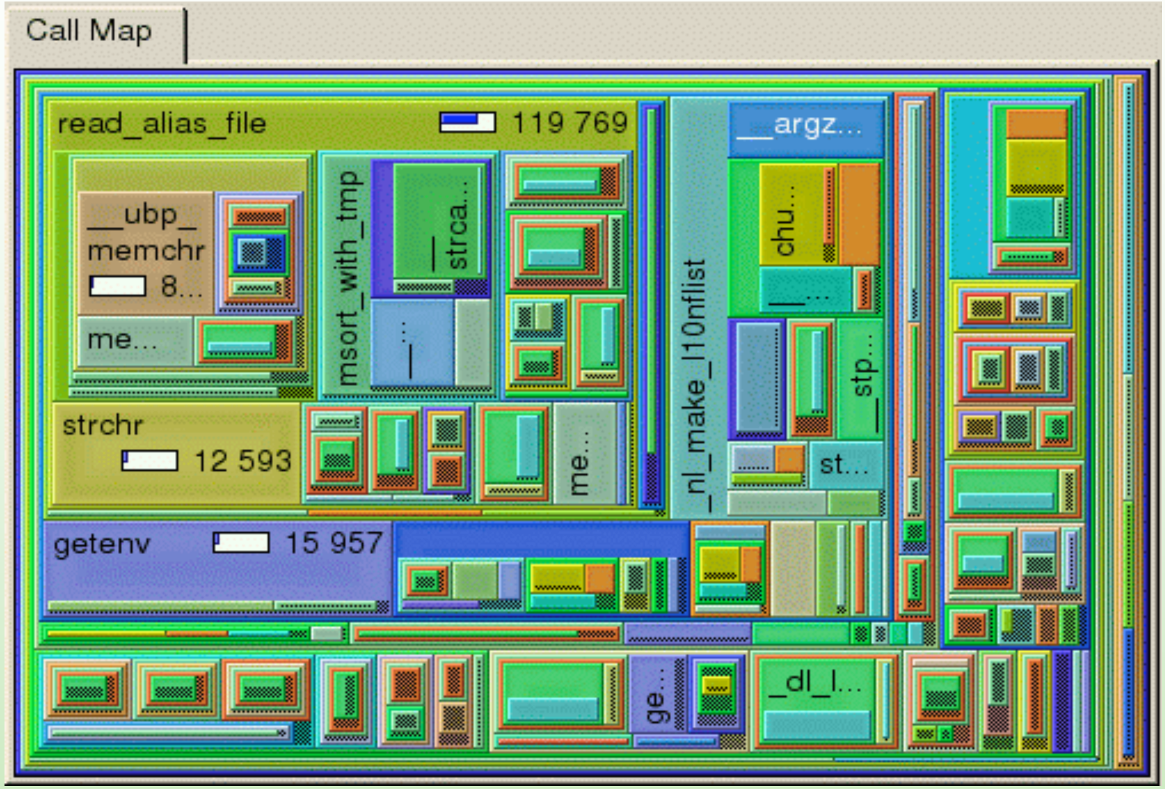
Callgrind: a call graph profiler

Callgrind

- Extension of Cachegrind
- By Josef Weidendorfer
- Also provides:
  - Call graph information
  - Graphical results viewer (KCachegrind)
    - Allows interactive browsing of results
    - Accepts Cachegrind results also
  - Greater selectivity of what code is profiled

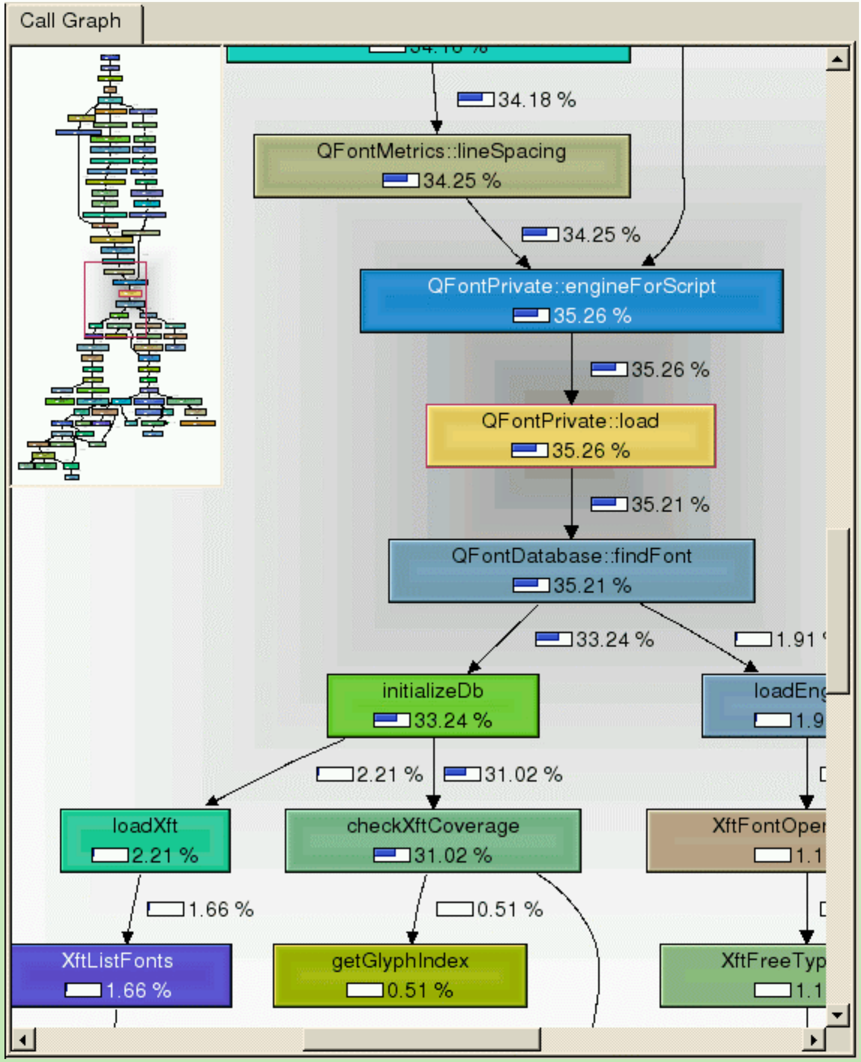


KCachegrind's tree-map view



- Box sizes represent relative counts
- Nesting of boxes represents call chains
- Interactive: can drill down through boxes

KCachegrind's call graph view



- Shows whole call graph
- Boxes show count proportions
- Interactive

Selective profiling

- Can dump counts at particular times
  - At termination (same as Cachegrind)
  - Periodically (every N code blocks)
  - At entry/exit of named functions
  - At particular program points (using client requests)
  - At any time (by invoking a separate script)
- Counters are zeroed after each dump
- Can choose which events to count
  - Instructions
  - Memory events (for cache simulation)
  - Function entries/exits

An interesting difficulty

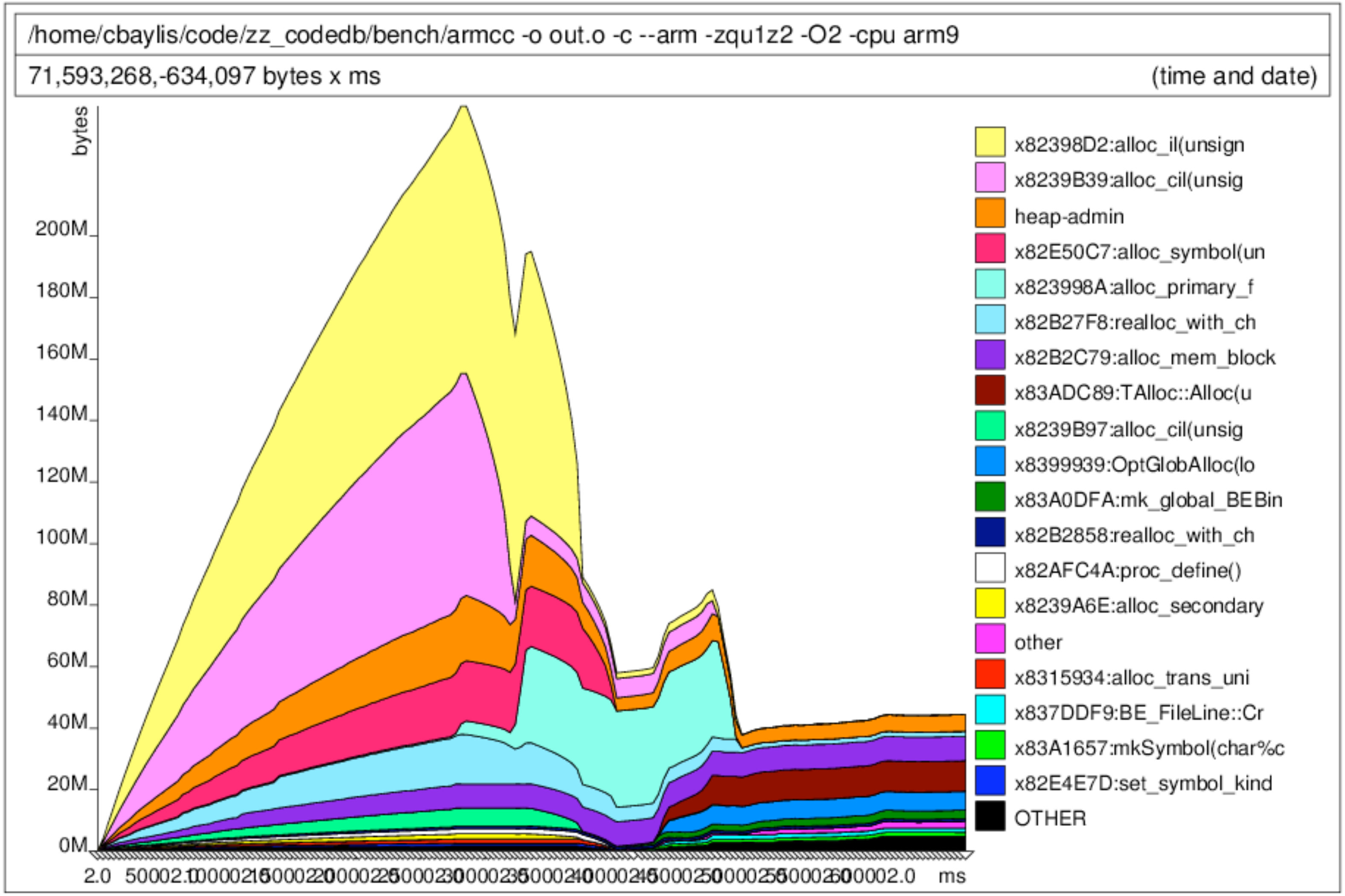
- Callgrind maintains a call stack
  - For tracking function entries/exits
- Several difficulties:
  - `setjmp/longjmp`
  - Tail recursion
  - Dynamic linking
    - Calls through jump tables
    - Jump table patched on first call after loading
  - Stack switching
- Missed entries/exits can throw everything out

Interesting lessons

- Good tools go beyond the basics
  - Results presentation
  - Analysis selectivity
- Some tool tasks are more difficult than you would expect

Massif: a heap profiler

Massif heap graph



Massif

- Measures heap and stack
  - Each heap allocation site is a band
  - Stack is a band
- Also produces HTML output
  - Represents the call graph underlying allocations
  - Users can drill down through calling chains from allocation sites
- Simple interaction with Valgrind's core
  - Only uses function wrapping
  - No instrumentation of code blocks
  - Complexity in the tool, not at the core/tool boundary

Summary

- Cachegrind, Callgrind, Massif
- Three different profilers
  - Not necessarily what you need
  - Demonstrate the kinds of things you can do
- Next: details of how to write a tool

(end of talk 2)

3. Building a new Valgrind tool

Nicholas Nethercote

This talk

- How to write a new tool from scratch
  - Simple but useful example: memory tracer
  - Start with simplest version
  - Improve its accuracy and performance

A new tool from scratch

Memtrace

- Example tool
- Trace memory (data) accesses
  - Loads, stores, modifies
- Print entry for each memory access
  - Data address
  - Data size

Tool basics

- Tools must provide functions for 3 tasks:
  - Initialization
  - Instrumentation
  - Finalization
- Analysis code can be added
  - Inline
  - Calls to C functions
- Tools provide functions that help the core provide certain services
  - E.g. error reporting, options processing

Build environment

- In what follows, all filenames are relative to top-level Valgrind directory
- Valgrind uses automake/autoconf
  - Use an SVN version of Valgrind; this simplifies Makefile handling
  - www.valgrind.org explains how to get the SVN version

Preliminaries

- Create empty directories:
  - `memtrace/`
  - `memtrace/docs/`
  - `memtrace/tests/`
- Create empty files:
  - `memtrace/docs/Makefile.am`
  - `memtrace/tests/Makefile.am`
- Copy `none/Makefile.am` to `memtrace/`
- Edit files:
  - Add three entries to `AC_OUTPUT` in `configure.in`:
    - `memtrace/Makefile`
    - `memtrace/docs/Makefile`
    - `memtrace/tests/Makefile`
  - Add `memtrace` to `TOOLS` in `Makefile.am`
  - Change names within `memtrace/Makefile.am` appropriately:
    - `s/none/memtrace/`
    - `s/nl_/mt_/`

First `mt_main.c` (1/3)

- Create `memtrace/mt_main.c`
  - Two-letter prefix is just a convention

```
#include "pub_tool_basics.h"      // Needed by every tool
#include "pub_tool_tooliface.h"   // Needed by every tool
#include "pub_tool_libcprint.h"   // For printing functions
#include "pub_tool_machine.h"     // For VG_(fnptr_to_fnentry)
```

- Most tool-visible headers in `include/pub_tool_*.h`
- Next: four functions must be defined
  - Pre-option-processing initialization
  - Post-option-processing initialization
  - Instrumentation
  - Finalization

First `mt_main.c` (2/3)

```
static void mt_pre_clo_init(void)
{
   // Required details for start-up message
   VG_(details_name)              ("Memtrace");
   VG_(details_version)           ("0.1");
   VG_(details_description)       ("a memory tracer");
   VG_(details_copyright_author)("Copyright (C) 2006, J. Random Hacker.");
   // Required detail for crash message
   VG_(details_bug_reports_to)   ("/dev/null");

   // Name the required functions #2, #3 and #4.
   VG_(basic_tool_funcs)          (mt_post_clo_init,
                                   mt_instrument,
                                   mt_fini);
}

// This prevents core/tool interface problems, and names the required
// function #1, giving the core an entry point into the tool.
VG_DETERMINE_INTERFACE_VERSION(mt_pre_clo_init)
```

First `mt_main.c` (3/3)

```
// Post-option-processing initialization function
static void mt_post_clo_init(void) { }

// Instrumentation function.  "bbIn" is the code block.
// Others arguments are more obscure and often not needed -- see
// include/pub_tool_tooliface.h.
static IRBB* mt_instrument ( VgCallbackClosure* closure,
                             IRBB* bbIn,
                             VexGuestLayout* layout,
                             VexGuestExtents* vge,
                             IRType gWordTy, IRType hWordTy )
{
    return bbIn;
}

// Finalization function
static void mt_fini(Int exitcode) { }
```

- (These functions must precede `mt_pre_clo_init`)

Build and test

- Build:

```
./autogen.sh
./configure --prefix=`pwd`/inst
make install
```

- Test:

```
inst/bin/valgrind --tool=memtrace date
```

  - Should run ok, but produce no output
- So far, almost identical to `none/nl_main.c`
  - Now ready for proper tool-writing

Vex IR

- Intermediate representation (Vex IR)
  - *Vex* is the name of the JIT compiler sub-system
  - Short code blocks (`IRBB`)
    - Represent roughly 3-50 instructions each
  - Arbitrary number of temporaries (intermediate values)
    - A block's *type environment* holds size of each temporary
  - Sequences of statements (with side-effects) (`IRStmt`)
    - E.g. stores, register writes
  - Statements contain expression trees (no side-effects) (`IRExpr`)
    - E.g. loads, arithmetic operations
    - E.g. a store's address and value are both expressions
  - Each block ends in a jump
- All IR-related details are in `VEX/pub/libvex_ir.h`
  - Included by `pub_tool_tooliface.h`, via `libvex.h`

`mt_instrument` (outer)

```
// include/pub_tool_basics.h provides types such as "Int".
Int i;

// Setup bbOut: allocate, initialize non-statement parts: type
// environment, block-ending jump's destination and kind.
IRBB* bbOut      = emptyIRBB();
bbOut->tyenv     = dopyIRTypeEnv(bbIn->tyenv);
bbOut->next      = dopyIRExpr(bbIn->next);
bbOut->jumpkind = bbIn->jumpkind;

// Iterate through statements, copy to bbOut, instrumenting
// loads and stores along the way.
for (i = 0; i < bbIn->stmts_used; i++) {
   IRStmt* st = bbIn->stmts[i];
   if (!st) continue;        // Ignore null statements
   // <Instrument loads and stores here (next 2 slides)>
   addStmtToIRBB(bbOut, st);
}
return bbOut;
```

mt_instrument (inner, 1/2)

```
switch (st->tag) {
 case Ist_Store: {
   // Pass to handle_store: bbOut, store address and store size.
   handle_store(bbOut, st->Ist.Store.addr,
      sizeofIRType(typeOfIRExpr(bbIn->tyenv, st->Ist.Store.data)));
   break;
 }
 case Ist_Tmp: { // A "Tmp" is an assignment to a temporary.
   // Expression trees are flattened here, so "Tmp" is the only
   // kind of statement a load may appear within.
   IRExpr* data = st->Ist.Tmp.data;  // Expr on RHS of assignment
   if (data->tag == Iex_Load) {      // Is it a load expression?
      // Pass handle_load bbOut plus the load address and size.
      handle_load(bbOut, data->Iex.Load.addr,
         sizeofIRType(data->Iex.Load.ty));  // Get load size from
   }                                         // type environment
   break;
 }

 // <One more case (see next slide)>
}
```

`mt_instrument` (inner, 2/2)

- "Dirty" statements represent unusual instructions, e.g. `cpuid`, `fxsave`
  - Avoids encoding highly architecture-specific details in the IR
  - Tools can still see the register and memory accesses done by the instruction, and so do basic instrumentation

```
case Ist_Dirty: {
  IRDirty* d = st->Ist.Dirty.details;
  if (d->mFx == Ifx_Read || d->mFx == Ifx_Modify)
     handle_load(bbOut, d->mAddr, d->mSize);
  if (d->mFx == Ifx_Write || d->mFx == Ifx_Modify)
     handle_store(bbOut, d->mAddr, d->mSize);
  break;
}
```

Adding calls to tracing functions

```
static void add_call(IRBB* bb, IRExpr* dAddr, Int dSize,
                     Char* helperName, void* helperAddr)
{
   // Create argument vector with two IRExpr* arguments.
   IRExpr** argv = mkIRExprVec_2(dAddr, mkIRExpr_HWord(dSize));
   // Create call statement to function at "helperAddr".
   IRDirty* di = unsafeIRDirty_0_N( /*regparms*/2, helperName,
                     VG_(fnptr_to_fnentry)(helperAddr), argv);
   addStmtToIRBB(bb, IRStmt_Dirty(di));
}
static void handle_load(IRBB* bb, IRExpr* dAddr, Int dSize) {
   add_call(bb, dAddr, dSize, "trace_load", trace_load);
}
static void handle_store(IRBB* bb, IRExpr* dAddr, Int dSize) {
   add_call(bb, dAddr, dSize, "trace_store", trace_store);
}
```

- (These functions must precede `mt_instrument`)

Run-time tracing functions

```
// VG_REGPARM(N): pass N (up to 3) arguments in registers on x86 --
// more efficient than via stack.  Ignored on other architectures.
static VG_REGPARM(2) void trace_load(Addr addr, SizeT size)
{
   VG_(printf)("load  : %08p, %d\n", addr, size);
}

static VG_REGPARM(2) void trace_store(Addr addr, SizeT size)
{
   VG_(printf)("store : %08p, %d\n", addr, size);
}
```

- (These functions must precede `handle_load` and `handle_store`)
- These functions called for every load and store at run-time
- `VG_(printf)` is Valgrind's `printf` function
  - Valgrind does not use libc
  - `VG_()` is a macro that prefixes a longer string to the name

Improving accuracy and speed

Improving Memtrace's accuracy

- Previous code treats "modify" instructions as a load + store
  - `addl %eax, (%ebx)` modifies `(%ebx)`
- Some instructions load/store multiple separate locations
  - `cmpsb` loads `(%esi)`, loads `(%edi)`
  - `pushl (%edx)` loads `(%edx)`, stores `-4(%esp)`
  - `movsw` loads `(%esi)`, stores `(%edi)`
- Collect load and store accesses for each instruction to identify memory access type, then instrument
  - `IMark` statements mark instruction boundaries in statement list
  - Modifies have a load and store to same address
  - Allows instruction reads to be traced as well
  - See `lackey/lk_main.c` for exactly this
- Could track loads/stores at system call boundaries

Improving Memtrace's speed

- C calls are expensive
  - Save/restore caller-save registers around call
  - Setup arguments
  - Jump to function and back
- Can group C calls together
  - E.g. common pairs like load/load, load/store, store/store
  - ~1/2 as many C calls to trace functions
  - ~1/2 as many calls to `VG_(printf)`

Improving speed in general

- C calls are expensive
  - Combine when possible
  - Use inline code where possible
    - Especially for simple things like incrementing a counter
- Do work at instrumentation-time, not run-time
  - Cachegrind stores unchanging info about each instruction (instr. size, instr. addr, data size if a load/store) in a struct, passes struct pointer to simulation functions
    - Fewer arguments passed, shorter, faster code
- Do work in batches
  - Eg. Instruction counter: increment by N at start of block, rather than by 1 at every instruction
- Compress repetitive analysis data

More about tool-writing

- Vex IR is powerful but complex
  - We have only scratched the surface
  - All IR details are in `VEX/pub/libvex_ir.h`
- Tool-visible headers, one per module:
  - `include/pub_tool_*.h`
  - `VEX/pub/libvex{,_basictypes,_ir}.h`
- About 30 tool-visible modules:
  - Header files provide best documentation
  - `coregrind/pub_core_<M>.h` also helps explain things about module `<M>`
- Existing tools (especially Lackey) are best guides

Summary

- Have seen how to build a very simple tool
- Next: ideas for more ambitious tools

(end of talk 3)

4. More advanced tools

Nicholas Nethercote

This talk

- Some interesting kinds of advanced tools
  - Shadow location tools
  - Shadow value tools
    - Example: Redux, a dynamic dataflow graph tracer
    - Idea: Bandsaw, a memory bandwidth profiler
- What can you do with a Valgrind tool

Shadow location & value tools

Shadow location tools

- Tools that shadow every register and/or memory *location* with a metavalue that says something about it
- Examples:
  - Memcheck: addressability of memory bytes
  - Eraser: lock-sets held when memory bytes accessed
  - Or, simpler: count how many times the location has been accessed
- Each shadow location holds an approximation of the history of its corresponding location

Shadow value tools

- Tools that shadow every register and/or memory *value* with a metavalue that says something about it
- Examples:
  – Memcheck: definedness of values
  – TaintCheck: taintedness of values
  – Annelid: bounds of pointer values
  – Hobbes: run-time types of values
- Each shadow value is an approximation of the history of its corresponding value

A powerful facility?

- Shadowing every location or value is expensive and difficult, but doable
  - Valgrind provides unique built-in support for it
  - Memcheck's slowdown factor is 10--60x
- What can you achieve by recording something about every location or value in a program?
  - Let us consider an illuminating example
  - Redux, a dynamic dataflow graph tracer

Two programs

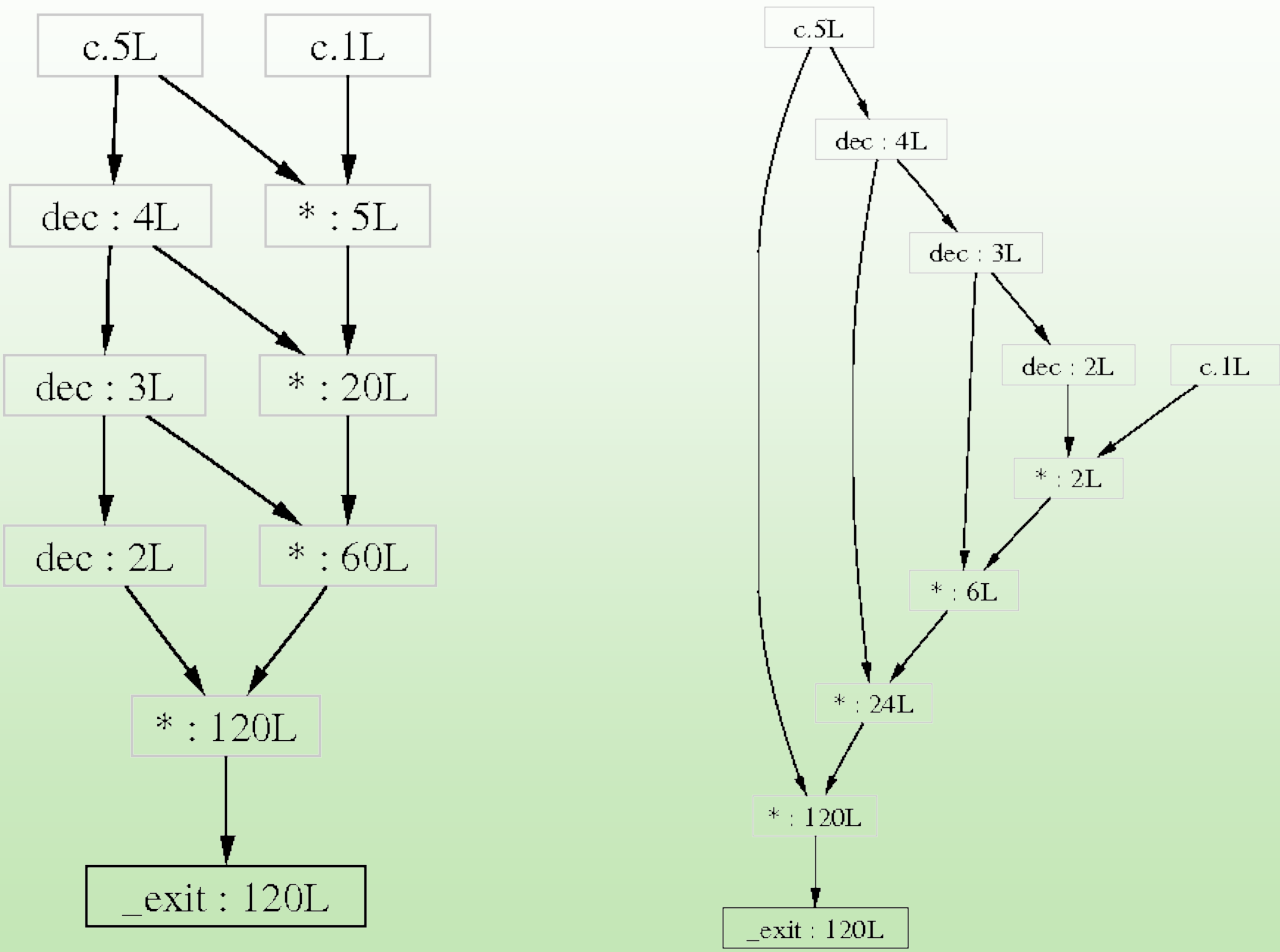
```c
int faci(int n)
{
   int i, ans = 1;
   for (i = n; i > 1; i--)
      ans = ans * i;
   return ans;
}

int main(void)
{
   return faci(5);
}
```

```c
int facr(int n)
{
   if (n <= 1)
      return 1;
   else
      return n * facr(n-1);
}

int main(void)
{
   return facr(5);
}
```

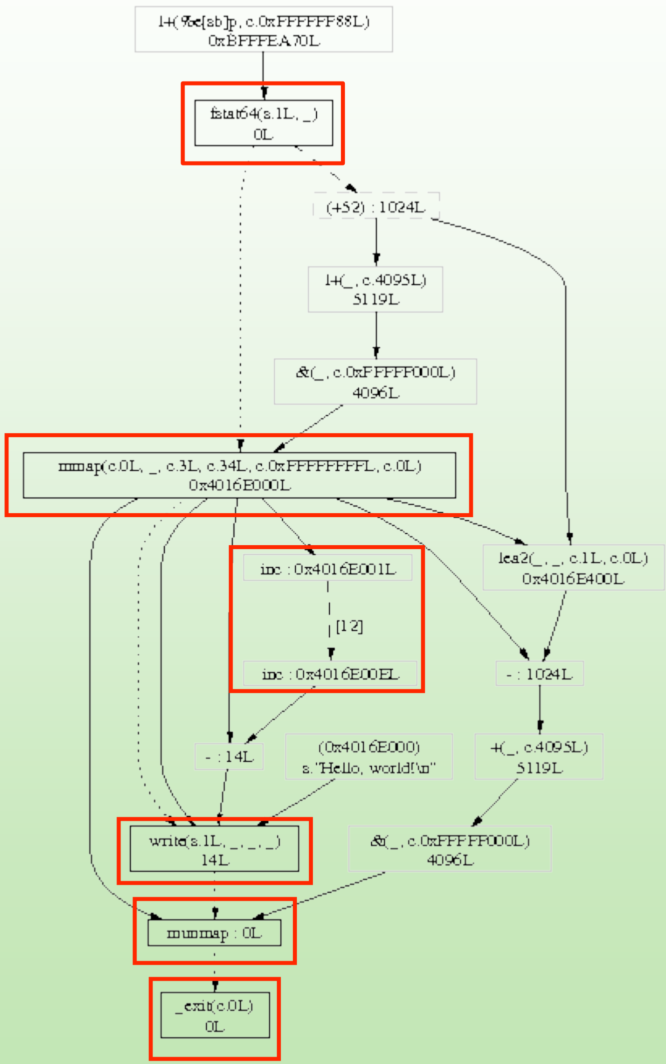
Two DDFGs


c.5L
c.1L
dec : 4L
* : 5L
dec : 3L
* : 20L
dec : 2L
* : 60L
* : 120L
_exit : 120L
c.5L
dec : 4L
dec : 3L
dec : 2L
c.1L
* : 2L
* : 6L
* : 24L
* : 120L
_exit : 120L

DDFG Features

- Each node represents a constant, or value-producing operation:
  - Arithmetic/logic instructions (add, sub, and, or, ...)
  - Address computation instructions (lea)
  - System calls
- Doesn’t show other operations:
  - Copies (register/register, register/memory)
  - Function calls, returns
  - Branches
- Only shows:
  - System call nodes (external behaviour)
  - Parts of graph reachable from system call nodes (data flow)
  - Interesting computations only! *No book-keeping*

Hello world



- `fstat64` checks stdout
- `mmap` allocates an output buffer
- String length is counted
- `write` prints the string
- `munmap` frees the output buffer
- `_exit` terminates program
- 29,000 nodes built, 17 shown!
  - Most in dynamic linker

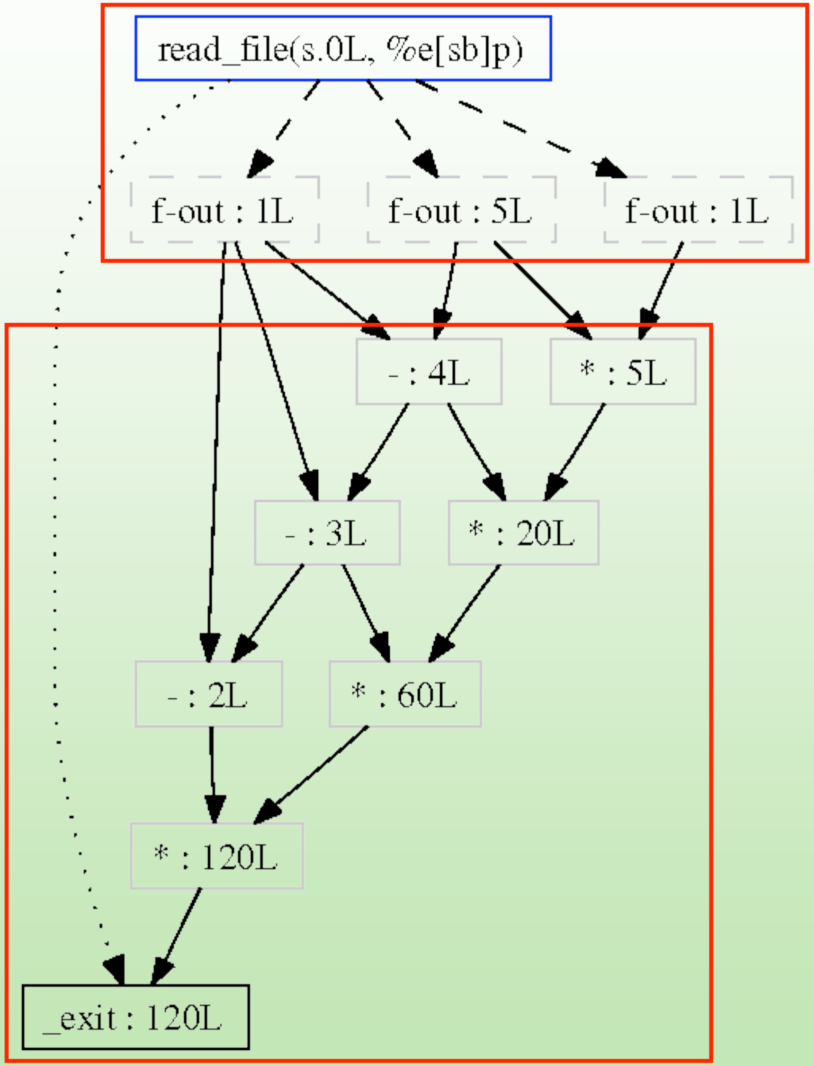
Essences

```
int faca(int n, int acc)
{
   if (n <= 1)
      return acc;
   else
      return faca(n-1, acc*n);
}

int main(void)
{
   return faca(5, 1);
}
```

- Accumulator recursion
- Algorithmically equivalent to iterative version
- Identical DDFGs

Stack machine version

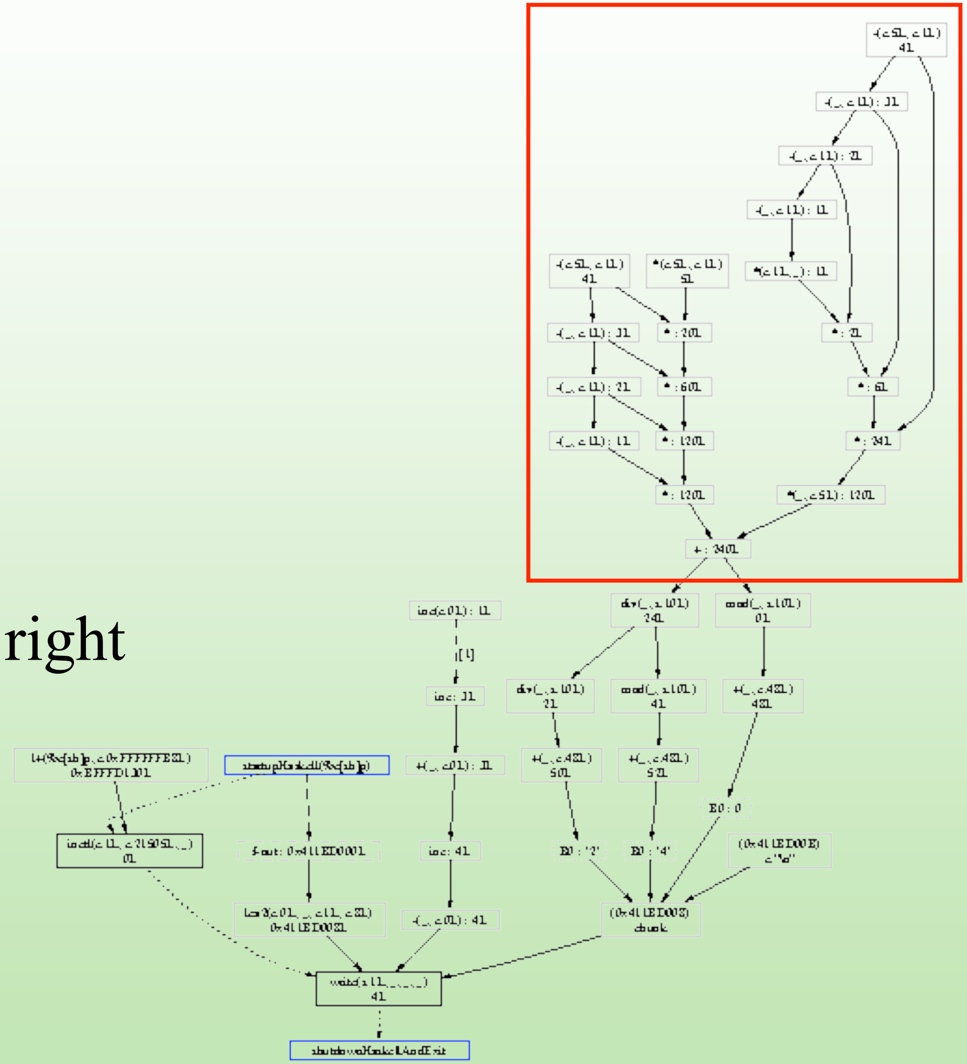


- *Folded* top node reads program, converts ASCII characters to integers (1, 1, and 5)
- Same as C version, except -(X,1) vs. dec(X)
- Very different computation model

Haskell version

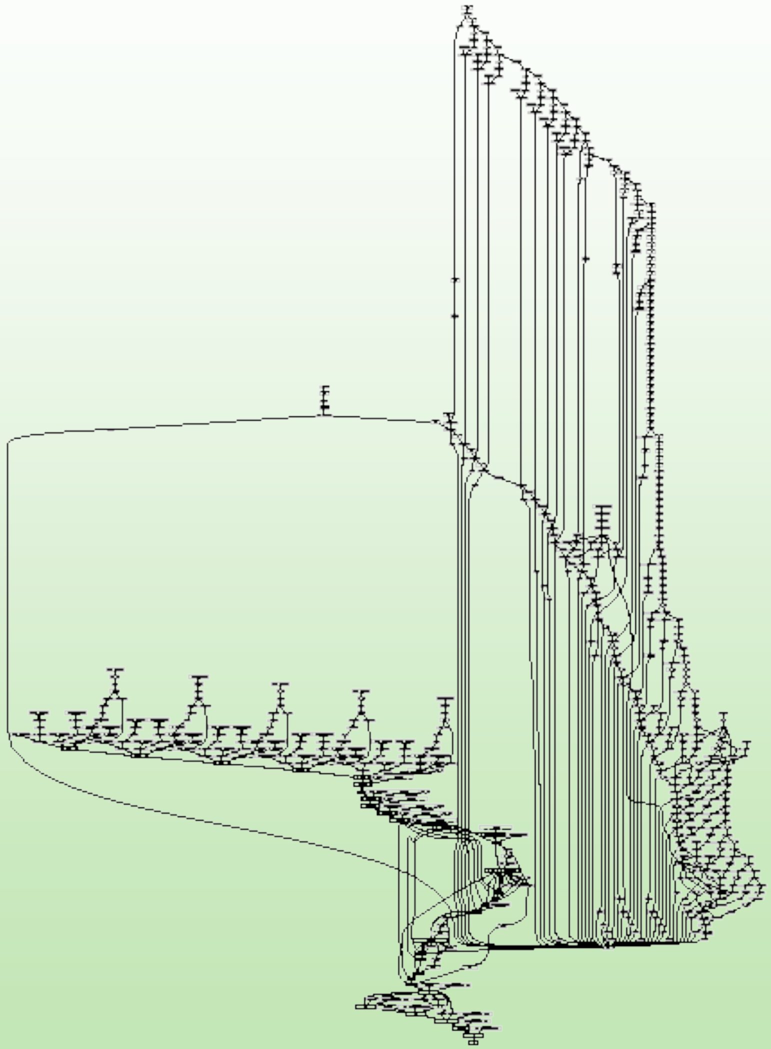
```
main =
  putStrLn
    (show
      (facr 5 +
       faca 5 1)
    )
```

- fac computations top right



Scaling difficulties

- bzip2'ing a two-byte file
  - dot: 8 seconds
  - ghostview: 5 seconds
- Scales terribly
  - CPU/memory use
  - Too big to view



Possible uses?

- Hmm, maybe:
  - Program visualisation
  - Debugging by sub-graph inspection
  - Dynamic slicing
  - Program comparison
- Really, grasping at straws
  - Too impractical as-is

So why talk about Redux?

- It is a good pedagogical tool
  - Explains dynamic binary analysis
  - Explains shadow value tools
  - Gets people thinking, generates ideas
    - “You can do anything” is too abstract
    - Makes the possibilities more concrete
- Shadow values are approximations of a value’s history
  - Redux shadow values show most of that history

Shadow value/location profilers

- All existing shadow value/location tools are error checkers
  - Except Redux
- Profiling shadow location tools?
  - Count how many times registers or memory locations accessed?
- Profiling shadow value tools?
  - Count how many times value has been copied?
- Something more interesting?

An idea: Bandsaw

- Show how data flows from place to place through memory
- Measure the amount of memory bandwidth used by each producer/consumer instruction pair

```
line A:  for (i = 0; i < 10*1000*1000; i++)
             a[i] = <...whatever...>
line B:  for (i = 0; i < 10*1000*1000; i++)
             sum += a[i];
```

- 40 MB transferred from line A to line B
- Shadow locations
  - Each memory location shadowed with instr. addr of its producer
  - Upon a read, increment the producer/consumer pair count
- Useful? Don't know… but shows what you can do

What can you do with a Valgrind tool?

Valgrind tools can…

- Delete, replace or augment every user-mode instruction
- Add analysis code inline, or as calls to C functions
- Wrap any system call
- Wrap any function
- Replace any function with a different one
- Observe or change any register or memory value

Instrumentation limitations

- Tools see Valgrind's IR, not original instruction stream
  - Allows platform-independent instrumentation
  - Some information is lost
  - But instruction boundaries are preserved
- Virtual addresses
- Microarchitecture not directly visible (e.g. pipelines, μ-ops)
  - Can simulate to a point (e.g. caches, branch predictors)

Some underlying concepts

- Profilers:
  - Concepts: X happened N times, X happened near Y
    - Cachegrind, Callgrind, Massif
- Checkers:
  - Concept: X happened so Y should/should not happen
    - Memcheck, Helgrind, TaintCheck, Annelid, Daikon
  - Concept: X and Y were true at the same time, so…
    - Data race detectors (Eraser, DRD)
- Visualizers:
  - Concept: X fed into Y
    - Redux
- These concepts are common, but not the only ones

Brainstorming for new tools

- Power consumption profiling (Valgrind too high-level?)
- Floating point analysis/tracking
  - Loss of precision, underflows, NaN propagation
- Global domain-specific constraints
  - Pre/post-conditions, e.g. pthreads
  - Resource allocation/deallocation tracking
- Fault/event injection
- Data flow profiling to guide hardware compilation
- De-compilation/de-obfuscation tools
- Test suite generation
- Analyse crypto code as it runs to extract keys?

Tool design is difficult

- Need output that programmers can directly act on
- Efficiency of analysis code is crucial
- In checkers: getting the false positive rate down is hard
- Compilers generate really strange code
  - So do humans
- Inferring high-level info from low-level code is hard
  - E.g. is that a stack switch or large local array?
- Simple tools are boring!
  - The good tools are 1000s of lines of code, not 10s or 100s
  - Instrumentation (basic data extraction) is often only a small part
  - Good tools do clever things with the extracted data
  - Ability to write an instruction counter in only 5 lines is overrated

Take-home message

What do you want to know?

- What do you want to know about program execution that existing tools cannot tell you?
- Valgrind lets you build powerful program analysis tools
  - Can you learn what you want about programs using shadow locations or shadow values?
  - Or any other Valgrind-supported feature?
- The best tools do not arise in a vacuum
  - Good: “I wish I knew X about my program…”
  - Bad: “I want to write a tool. What would be a good one?”
- You are the people with the “I wish I knew X” ideas
  - Let your imaginations loose
  - Talk to the tool-makers
  - Maybe your idea is possible

Acknowledgments

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(end of talk 4)