Valgrind, Dynamic Binary Instrumentation and what you can do with it

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My Background

- Chair for computer architecture at CS faculty, TUM
  - how to exploit current & future (HPC) systems (multicore, accelerators)
  - programming models, performance analysis tools, application tuning
- PhD on load balancing of commercial car crash code (MPI) 2003
- Interested especially in cache analysis and optimization
  - cache simulation: Callgrind (using Valgrind)
  - applied to 2D/3D stencil codes
  - recently extended to multicore (additional bottlenecks, new benefits)

What is Valgrind?

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 (most widely used tool), often call just “Valgrind”

Analysis Tools

Categorization 1: when does analysis occur?

- before run-time: static analysis
  - needs parsing (addition to compiler)
  - imprecise, but can be sound: sees all execution paths
- at run-time: dynamic analysis
  - needs instrumentation = inject analysis code into code
  - powerful, but unsound: sees one execution path

Valgrind performs dynamic analysis

Analysis Tools

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 to show source code)
  - lower-level information: e.g. registers, instructions

Valgrind performs binary analysis

What is Valgrind?

Valgrind: Dynamic binary analysis (DBA)

- analysis of machine code at run-time
- instrument original code with analysis code
  (= Dynamic Binary Instrumentation, DBI)
- track some extra information: metadata
- do some extra I/O, but don’t disturb execution

DBI frameworks:

- Pin, DynamoRIO, DIOTA, DynInst, etc.
- lots of overlap
- each system supports different platforms

Valgrind Basics

- dynamic binary instrumentation infrastructure
  - allows to build tools able to observe / modify the execution of programs
  - works at the binary level at runtime (no recompilation needed)

- supports Linux/AIX/OS-X on x86, x86-64, PPC32/64, ARM, MIPS

- correctness checking & profiling tools on top
  - “memcheck”: accessibility/validity of memory accesses
  - “helgrind” / ”drd”: race detection on multithreaded code
  - “cachegrind”/”callgrind”: cache & branch prediction simulation
  - “massif”: memory profiling

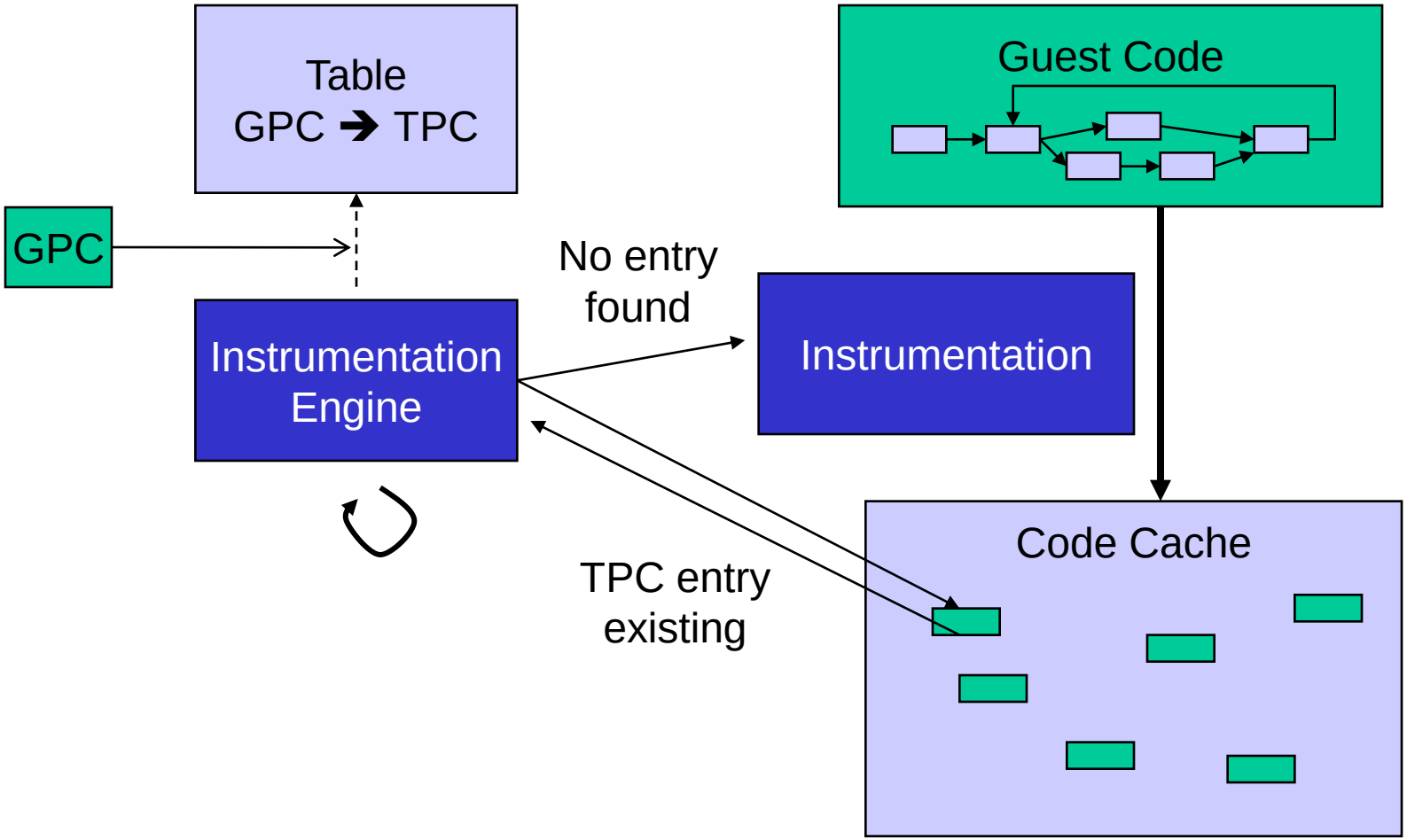
- Open source (GPL), www.valgrind.org, current version 3.9.0

How does Valgrind work?

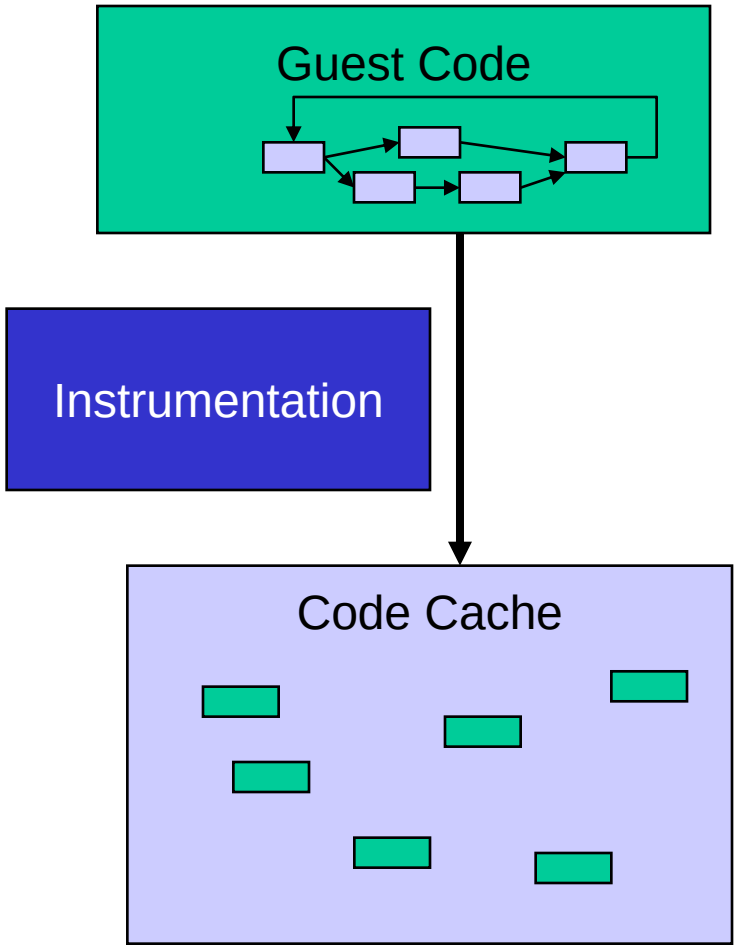
Dynamic Runtime Instrumentation

- full control of the execution of a program (“guest code”)
- loads guest into same process, but never run original code
- piece-wise controlled execution of instrumented original code
- granularity of instrumentation:
  dynamic basic block (BB): instruction sequence ending at branch
- loop in instrumentation engine:
  - for next guest PC (GPC) to execute: BB at GPC already translated?
  - if not: generate translated/instrumented version, store into code cache (may throw away old translations if cache is full)
  - run translated BB corresponding to GPC from code cache
  - translated BB returns next GPC to execute

Dynamic Runtime Instrumentation



Dynamic Runtime Instrumentation



ISA: x86, ARM, MIPS, …

↓

VG VEX Bytecode

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Tool Instrumentation Function

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VG VEX Bytecode

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ISA: x86, ARM, MIPS, …

How does it Valgrind work? (cont.)

Custom tools need to provide 3 functions:

- instrumentation function
  - input: list of VEX instructions from BB to instrument
  - output: list of VEX instructions of instrumented version
  - instructions are abstracted from ISAs to allow platform independence (this V-ISA/bytecode is called “VEX”)
- initialization:
  called at the very beginning to allocate own memory
- finalization:
  called at program termination

How does Valgrind work? (cont.)

Typical instrumentation: loop over instructions

- add additional instructions depending on instruction type
- also needs to add the original instruction into output sequence (this allows modification)
- added instructions may be CALLs into own code

```
// 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];
// Add your own instrumentation
addStmtToIRBB(bbOut, st);
}
return bbOut;
```

Example Instrumentation Function

```
switch (st->tag) {
 case Ist_Store: {
   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
   }
   break;
   ...
}
```

Example Instrumentation Function

- “Dirty” statements represent unusual instructions, e.g. cpuid, fxsave
  - avoids encoding highly architecture-specific details in VEX
  - 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;
}
```

How does Valgrind work? (cont.)

With dynamic instrumentations, 3 types of times can be distinguished

- compilation time: no runtime information known
  - original code, generated by comiler
- instrumentation time: usually happening once, directly before exec.
  - partial runtime information known, may be used for optimizations
  - code shown on previous slides
- execution time
  - code run when instrumented code is executing itself

Example: Still Instrumentation Time

```
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);
}
```

Example: Functions called at Execution Time

```
/ 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);
}
```

Starting Up

- Valgrind
  - loads the core, chosen tool and guest 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
  - 3x times rewritten!

Complications

- System calls
  - Valgrind does not trace into kernel
  - calls to custom before/after handlers can be requested
  - Valgrind knows about input/output of all Linux syscalls
- Signals
  - interception at registration/delivery needed
- Threads
  - get serialized by Valgrind

Client Requests

- Trap-door mechanism
  - An unusual no-op instruction sequence
  - Under Valgrind, it transfers control to core/tool
  - guest 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 macro
  - Tools only need to include a header file to use them
  - They do nothing when running natively

More Complex Tools

- Slowdown
  - naïve way: easily > 100x
  - optimization: merge/spezialize at instrumentation time
- meta information
  - VG provides “shadow memory”
  - arbitrary meta information for every original memory cell
    - memcheck: valid / initialized?

Pro & Contra (i.e. Simulation vs. Real Measurement)

Usage of Valgrind

- – driven only by user-level instructions of one process
- – slowdown (call-graph tracing: 15-20x, + cache simulation: 40-60x)
  - “fast-forward mode”: 2-3x
- ✓ allows detailed (mostly reproducable) observation
- ✓ does not need root access / can not crash machine

Example Callgrind: Simple Cache model

- – “not reality”: synchronous 2-level inclusive cache hierarchy (size/associativity taken from real machine, always including LLC)
- ✓ easy to understand / reconstruct for user
- ✓ reproducible results independent on real machine load
- ✓ derived optimizations applicable for most architectures

Questions?

Backup

Numerical Stability of Algorithms

- Setting/Forcing FP Rounding Modes in VEX

```
/* Variants of the above which produce a 64-bit result but which
        round their result to a IEEE float range first. */
/* :: IRRoundingMode(I32) x F64 x F64 -> F64 */
      Iop_AddF64r32, Iop_SubF64r32, Iop_MulF64r32, Iop_DivF64r32,
```

- Catch FP Ops in own instrumentation function
  - replace rounding mode by wished one

- Unfortunately, this currently works only with ARM/PPC
- x86 is missing correct handling in
  - frontend: rounding not correctly set (easy)
  - backend: generate optimized x86 code to set requested mode

KCachegrind: Usage

```
{k,q}cachegrind callgrind.out.<pid>
```

- left: “Dockables”
  - list of function groups groups according to
    - library (ELF object)
    - source
    - class (C++)
  - list of functions with
    - inclusive
    - exclusive costs
- right: visualization panes