DBrew – A Library for Dynamic Binary Rewriting

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Work together

with colleagues

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with student

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About me

Computer Architecture Chair at TUM with focus on HPC

Interested in

• Performance Analysis Tools & Optimization Strategies (cache simulation Callgrind, recently multi-core NUMA)
• parallel programming models (e.g. PGAS)
• optimization techniques involving code generation
Code Generation

• in Valgrind (or Pin): Dynamic Binary Instrumentation
  – original binaries, instrumentation drives simulation

• project with ABB: improve performance in evaluation of large expression trees
  – interpreting bytecode vs. LLVM usage vs. manual generation

• performance optimizations SpMV, > 2GB CSR matrix
  – medical imaging (MLEM algorithm for PET): random structure
  – transform SpMV in 4GB linear code, code generator hand-tuned
  – do code generation & execution on-chip, sustained 8 GB/s
  – improvements > x2 (no indirection, no loop overhead)
Code Generation: Lessons Learned

Powerful technique if
• best performance depends on dynamic input data
• problem specific, hand-tuned generator is feasible
• programmer-controllable (algorithm/tuning knowledge)

Large Benefits from
• specialized code vs. generic code (similar to “compiled vs. interpreted”)
• code without lots of prologs/epilogs/loop overhead
Less-Manual Code Generation: Alternatives

Dispatch into statically generated variants
- using C++ templates (pre-processor macros with C)
- often too many variants (code explosion)

Generic JIT techniques
- generate LLVM-IR, use JIT at runtime / JS with V8
- not easy to control variant generation

New language (feature)
- difficult to sell to HPC community, no incremental use possible to improve existing legacy code
- we are not compiler guys
Use Cases for HPC
How about we add another layer of abstraction?

[from our HIPS16 paper on DBrew]
Use Cases for HPC

• Code generation can remove dynamic overhead of abstractions/generalizations in programming models
Use Cases for HPC

Introduce abstractions which enable optimizations

- concrete implementation not statically decided but only at runtime
  - examples: traversal orders, data layouts, partitioning
  - depending on target architecture, input data/intermediary results

- generic application code gets specialized for dynamic decisions at runtime

- application code decoupled from tuning heuristics

Others

- enable high-performance MPI data types
Dynamic Code Transformation for Programmers?

- incremental usage with existing HPC software stacks (C/C++/Fortran)
  - API / library to be linked to binary
  - machine code level (enables use with 3rd party compiled code)
- low-level machinery to generic code generation
  - for use by higher-level library layers / (compiler) runtimes
  - ISA-agnostic interface
  - transformation of existing code
- can be best-effort
  - only performance-relevant: if transformation fails, use original (enough to cover ISA instructions used in hot paths)
- failed transformations must not be catastrophic
- no additional complexity for debugging

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Dynamic Code Transformation for Programmers?

Existing tools: not directly usable

- dynamic x86 assembler libraries: too low-level
- LLVM
  - needs lot of meta information to be usable
    (to be provided by programmer/reconstructed by analysis)
  - large dependency
- Valgrind/Pin/DynamoRIO
  - use decoder/IR manipulation/generation, but not exposed
  - to observe binaries from outside, not to be used inside
- DynInst
  - to observe binaries from outside, not to be used inside

→ do our own library (may use existing tools internally)
What is DBrew?

- API to transform native, compiled code at runtime
- generate new variants of already existing functions
- provides drop-in replacements of original functions

Example (in C)

```c
#include "dbrew.h"
...
typedef int (*f_t)(int,int);
...
dbrew_set_func(f);
f_t ff = dbrew_rewrite(x1,x2);
...
a = f(p1, p2);
```

```c
a = (*ff)(p1, p2);
```
What is DBrew?

- currently x86-64 only
- github.com/lrr-tum/dbrew
- prototyping state
- examples should work
- any feedback welcome
DBrew Design

Configuration
• based on ABI (application binary interface: calling convention)
• information about values (esp. function parameters)
• control over transformation (inlining, loop unrolling)
• used resources (buffer sizes, code buffer)
• failure handling

Failures
• decode error, buffer overflow, …
• robust: on failure, may return/branch to original code
• other failure handling: enlarge buffers, restrict inlining, …
DBrew Configuration: Information on Values

Values

• function parameters (identified via ABI)
• global variables (via address)
• reachable via pointers being function parameters

Possible information (e.g. for int value “x”)

• known to be constant (“x = 5”)
  – enables evaluation of all operations with known values
• fulfilling conditions (“x > 5”)
  – restricts possible execution paths
• being most likely a given value (“x often is 5”)
  – influences inlining (needs a guard)
DBrew Configuration: Control of Transformation

Inline or call into given functions?
• functions are specified via their function address (the symbol name resolves to the address)
• on call instruction
  – call original function, or
  – trigger rewriting and redirect call to rewritten function
• black list / white list of functions allowed to be inlined
• restriction on call depths for inlining
Transformation: Spezialization using Known State

• maintain “known-ness” of registers / stack frame content
  – memory defaults to being unknown (unless configured)

• known values make transformed code more specialized
  – “known-ness” information can deliberately be thrown away

• same code to be transformed for different “known-ness” state may produce different results
  – may result in “run-away” traversals ➔ buffer overflow
  – automatically provides loop unrolling
  – restricted by migrating known to unknown state
    (by inserting “compensation code”)
    ➔ configuration: prohibit loop unrolling
Transformation: Traversal

Traverse all reachable execution paths

- **non-branch instructions**
  - only known operands: emulated, no resulting code generated (constant propagation)
  - otherwise: forward to resulting code, embed known values

- **branch with known target**
  - proceed unless configured otherwise (over calls: inlining)

- **branch with unknown targets**
  - generate new paths to traverse
  - start new block to transform
  - merge points for backward jumps (for same known-ness)
  - “ret”: finish path, forward “ret”, proceed with next path
Transformation: Example

C code and resulting compiled machine code (AT&T):

```c
int foo(int i, int j) {
    if (i == 5) return 0;
    return i+j;
}
```

```asm
<foo>:  
    add    %edi,%esi  
    mov    $0x0,%eax  
    cmp    $0x5,%edi  
    cmovne %esi,%eax  
    ret
```

Request transformation specializing for 1st par set to 2:

```c
dbrew_set_func(foo);

dbrew_set_staticpar(0); // 1st parameter known
foo_t f = (foo_t) dbrew_rewrite(2, 3);
```
Transformation: Example – Debug Output

Static State:
Registers: %rsp (R 0), %rdi (0x2), %rip = 400a40

<foo>:
  add %edi,%esi
  mov $0x0,%eax
  cmp $0x5,%edi
  cmovne %esi,%eax
  ret

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Transformation: Example – Debug Output

Static State:
Registers: %rsp (R 0), %rdi (0x2), %rip = 400a40

Process '0x400a40: add %edi,%esi'
Capture 'add $0x2,%esi' (into 0x400a40|0 + 1)
Static State:
Registers: %rsp (R 0), %rdi (0x2), %rip = 400a42

<foo>:
  add %edi,%esi
  mov $0x0,%eax
  cmp $0x5,%edi
  cmovne %esi,%eax
  ret
Transformation: Example – Debug Output

Static State:
  Registers: %rsp (R 0), %rdi (0x2), %rip = 400a40

Process '0x400a40: add %edi,%esi'
Capture 'add $0x2,%esi' (into 0x400a40|0 + 1)
Static State:
  Registers: %rsp (R 0), %rdi (0x2), %rip = 400a42

Process '0x400a42: mov $0x0,%eax'
Static State:
  Registers: %rax (0x0), %rsp (R 0), %rdi (0x2), %rip = 400a47

<foo>:
  add %edi,%esi
  mov $0x0,%eax
  cmp $0x5,%edi
  cmovne %esi,%eax
  ret
Transformation: Example – Debug Output

Static State:
   Registers: %rsp (R 0), %rdi (0x2), %rip = 400a40

Process '0x400a40: add %edi,%esi'
Capture 'add $0x2,%esi' (into 0x400a40|0 + 1)
Static State:
   Registers: %rsp (R 0), %rdi (0x2), %rip = 400a42

Process '0x400a42: mov $0x0,%eax'
Static State:
   Registers: %rax (0x0), %rsp (R 0), %rdi (0x2), %rip = 400a47

Process '0x400a47: cmp $0x5,%edi'
Static State:
   Registers: %rax (0x0), %rsp (R 0), %rdi (0x2), %rip = 400a4a
   Flags: CF (1) ZF (0) SF (1) OF (0) PF (0)
Transformation: Example – Debug Output

Static State:
  Registers: %rsp (R 0), %rdi (0x2), %rip = 400a40

Process '0x400a40: add %edi,%esi'
Capture 'add $0x2,%esi' (into 0x400a40|0 + 1)
Static State:
  Registers: %rsp (R 0), %rdi (0x2), %rip = 400a42

Process '0x400a42: mov $0x0,%eax'
Static State:
  Registers: %rax (0x0), %rsp (R 0), %rdi (0x2), %rip = 400a47

Process '0x400a47: cmp $0x5,%edi'
Static State:
  Registers: %rax (0x0), %rsp (R 0), %rdi (0x2), %rip = 400a4a
  Flags: CF (1) ZF (0) SF (1) OF (0) PF (0)

Process '0x400a4a: cmovnz %esi,%eax'
Capture 'mov %esi,%eax' (into 0x400a40|0 + 2)
Static State:
  Registers: %rsp (R 0), %rdi (0x2), %rip = 400a4a, %rip = 400a4d
  Flags: …
Transformation: Example – Result

\[<\text{foo}>:\]
\begin{align*}
\text{add} & \quad \%edi,\%esi \\
\text{mov} & \quad $0x0,\%eax \\
\text{cmp} & \quad $0x5,\%edi \\
\text{cmovne} & \quad \%esi,\%eax \\
\text{retq} & \quad \\
\end{align*}

\[<\text{foo}>:\]
\begin{align*}
\text{add} & \quad $0x2,\%esi \\
\text{mov} & \quad \%esi,\%eax \\
\text{ret} & \quad \\
\end{align*}

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First Results

Directly generate machine code after transformation

Optimizations missing yet
• register renaming after inlining
  (values in registers used for parameters often may get saved/restored)
• reduce stack spilling by using registers freed due to specialization
• …

Still should work already quite well
• we transform existing optimized machine code
First Results: Generic 2d stencils

Stencil s5 = {5, { { 0, 0, .4},
{ -1, 0, .1},
{ 1, 0, .1},
{ 0, -1, .1},
{ 0, 1, .1} }};

double apply(double *m, int xsize, Stencil* s)
{
    double res;
    int i;

    res = 0;
    for (i=0; i<s->points; i++) {
        StencilPoint* p = s->p + i;
        res += p->factor * m[p->xdiff + p->ydiff * xsize];
    }
    return res;
}
First Results: Generic 2d stencils

BB 0x7fc4c4b90000 (17 instructions):

- 0x7fc4c4b90000: c5 f9 57 c0 vxorpd %xmm0,%xmm0,%xmm0
- 0x7fc4c4b90004: c5 fb 10 0f vmovsd (%rdi),%xmm1
- 0x7fc4c4b90008: c5 f3 59 0c 25 18 71 vmulsd 0x627118,%xmm1,%xmm1
- 0x7fc4c4b9000f: c5 f3 59 0c 25 18 71 vmulsd 0x627118,%xmm1,%xmm1
- 0x7fc4c4b90011: c5 fb 58 cl vaddsd %xmm1,%xmm0,%xmm0
- 0x7fc4c4b90015: c5 fb 10 4f f8 vmovsd -0x8(%rdi),%xmm1
- 0x7fc4c4b9001a: c5 f3 59 0c 25 28 71 vmulsd 0x627128,%xmm1,%xmm1
- 0x7fc4c4b90021: 62 00
- 0x7fc4c4b90023: c5 fb 58 cl vaddsd %xmm1,%xmm0,%xmm0
- 0x7fc4c4b90027: c5 fb 10 4f 08 vmovsd 0x8(%rdi),%xmm1
- 0x7fc4c4b9002c: c5 f3 59 0c 25 38 71 vmulsd 0x627138,%xmm1,%xmm1
- 0x7fc4c4b90033: 62 00
- 0x7fc4c4b90035: c5 fb 58 cl vaddsd %xmm1,%xmm0,%xmm0
- 0x7fc4c4b90039: c5 fb 10 8f b0 e0 ff vmovsd -0x1f50(%rdi),%xmm1
- 0x7fc4c4b90040: ff
- 0x7fc4c4b90041: c5 f3 59 0c 25 48 71 vmulsd 0x627148,%xmm1,%xmm1
- 0x7fc4c4b90048: 62 00
- 0x7fc4c4b9004a: c5 fb 58 cl vaddsd %xmm1,%xmm0,%xmm0
- 0x7fc4c4b9004e: c5 fb 10 8f 50 1f 00 vmovsd 0x1f50(%rdi),%xmm1
- 0x7fc4c4b90055: 00
- 0x7fc4c4b90056: c5 f3 59 0c 25 58 71 vmulsd 0x627158,%xmm1,%xmm1
- 0x7fc4c4b9005d: 62 00
- 0x7fc4c4b9005f: c5 fb 58 cl vaddsd %xmm1,%xmm0,%xmm0
- 0x7fc4c4b90063: c3 ret
First Results: Generic 2d stencils

Matrix $1002^2$ elements, $1000^2$ updates, 1000 iterations
Intel(R) Core(TM) i7-3740QM CPU @ 2.70GHz

Generic version: 7.4 s
Rewritten: 3.5 s
Manual 5p version: 2.9 s

Grouped factors (nested loop, outer over factors)
Generic version: 8.5 s
Rewritten: 2.8 s

Always called via function pointers (!): no vectorization…
DBrew Snippets

Snippets
- short functions provided by DBrew
- semantic is known to DBrew (obviously)
- if called in code to be transformed, snippets can
  - specify DBrew configuration or meta information
  - may do different things depending on configuration
  - can be replaced with semantically identical code

Example
- mark an int value to become known on rewriting
  ```c
  int dbrew_mark_known(int i) { return i; }
  ```
  (this is basically a NOP when inlined)
DBrew Vectorization

Transform a scalar kernel into a vectorized variant
• input parameter is marked to be a scalar FP
• generates a variant with the parameter being a vector
• all operations on the “to-be-vectorized” value will be replaced by element-wise vector operations
  – example (x86 AVX): vmulsd $\rightarrow$ vmulpd

How to call vectorized variant?
• via DBrew snippet which adapts to expansion done (may depend on architecture: x2 for SSE, x4 for AVX)
DBrew Vectorization: Example

Kernel

double add_kernel(double v1, double v2)
{ return v1 + v2; }

Snippet

void dbrew_apply4_R8V8V8(dbrew_func_R8V8V8_t f,
    double* ov, double* i1v, double* i2v)
{   ov[0] = (f)(i1v[0], i2v[0]);
    ov[1] = (f)(i1v[1], i2v[1]);
    ov[2] = (f)(i1v[2], i2v[2]);
    ov[3] = (f)(i1v[3], i2v[3]); }

Usage

void vadd(double* dst, double* src1, double* src2, int n)
{   for(; n>0; n-=4, dst+=4, src1+=4, src2+=4)
        dbrew_apply4_R8V8V8(add_kernel, dst, src1, src2); }
**DBrew Vectorization: Example**

Transform vadd to use vectorized add kernel (AVX)

```c
dbrew_set_func(vadd);
dbrew_set_vectorsize(32);
vadd32 = (vadd_t) dbrew_rewrite(a, b, c, len);
```

Results for 20 iterations of vadd (10 mio elements)

- naïve (simple C loop): 0.40 s
- un-transformed snippet: 0.43 s
- rewritten-16 (SSE): 0.36 s
- rewritten-32 (AVX): 0.35 s

(AVX has unneeded prolog/epilog)
Experiments with LLVM

Experimental backend
• translate transformed code into LLVM-IR
• use LLVMs JIT code generator

Results for 2d stencil variants

Experiences
• DBrew does well
• much meta info required (signatures, pointers vs. int)
• useful LLVM opts

Benefits

![Bar chart showing run times for different methods.](chart.png)

(a) Running times where a single element is computed in one step.
Future Work

Internals
• low-hanging optimizations in own generator backend
• use 3rd-party decoders/generators (e.g. Valgrind VEX)
• validation: transformations correct?

Usage
• minimize the overhead of dynamic data distributions
• abstractions for iteration spaces, dynamic data layout

Discussion
• other usages
• better user interface (in C++, …)
Thanks – Questions?

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