Software Tools for Mixed-Precision Program Analysis

Mike Lam

James Madison University
Lawrence Livermore National Lab
About Me

- Ph.D in CS from University of Maryland ('07-'14)
  - Topic: Automated floating-point program analysis (w/ Jeff Hollingsworth)
  - Intern @ Lawrence Livermore National Lab (LLNL) in Summer ’11

- Assistant professor at James Madison University since '14
  - Teaching: computer organization, parallel & distributed systems, compilers, and programming languages
  - Research: high-performance analysis research group (w/ Dee Weikle)

- Faculty scholar @ LLNL since Summer '16
  - Energy-efficient computing project (w/ Barry Rountree)
  - Variable precision computing project (w/ Jeff Hittinger et al.)
• IEEE floating-point arithmetic
  – Ubiquitous in scientific computing
  – More bits => higher accuracy (usually)
  – Fewer bits => higher performance (usually)
Motivation

- Vector single precision 2X+ faster
  - Possibly better if memory pressure is alleviated
  - Newest GPUs use mixed precision for tensor ops

<table>
<thead>
<tr>
<th>Operation</th>
<th>FP32</th>
<th>Packed FP32</th>
<th>FP64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Subtract</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Multiply</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Divide</td>
<td>27</td>
<td>32</td>
<td>42</td>
</tr>
<tr>
<td>Square root</td>
<td>28</td>
<td>38</td>
<td>43</td>
</tr>
</tbody>
</table>

**Instruction latencies for Intel Knights Landing**

Credit: https://agner.org/optimize/ and NVIDIA Tesla V100 Datasheet
Questions

• How many bits do you need?
• Where does reduced precision help?
Prior Approaches

- **Rigorous**: forwards/backwards error analysis
  - Requires numerical analysis expertise
- **Pragmatic**: “guess-and-check”
  - Requires manual code conversion effort

```c
//double x[N], y[N];
float x[N], y[N];
double alpha;
```
Research Question

• What can we learn about floating-point behavior with **automated** analysis?
  – Specifically: can we build *mixed-precision* versions of a program automatically?

• Caveat: few (or no) formal guarantees
  – Rely on user-provided representative run (and sometimes a verification routine)

```c
double sum = 0.0;
void sum2pi_x()
{
    double tmp;
    double acc;
    int i, j;

    [...]  

    double sum = 0.0;
void sum2pi_x()
{
    float tmp;
    float acc;
    int i;
    int j;

    [...]  
```
FPAnalysis / CRAFT (2011)

- Dynamic binary analysis via Dyninst
- Cancellation detection
- Range (exponent) tracking

3.682236
- 3.682234
0.000002
(6 digits cancelled)
CRAFT (2013)

- Dynamic binary analysis via Dyninst
- Instruction-level replacement of doubles w/ floats
- Hierarchical search for valid replacements

Diagram:
- Program structure with functions and instructions.
- Binary modification process flow diagram.
if (timers_enabled) call timer_start(2)

do 140 i = 1, nk
    x1 = 2.d0 * x(2*i-1) - 1.d0
    x2 = 2.d0 * x(2*i) - 1.d0
    t1 = x1 ** 2 + x2 ** 2
    if (t1 .le. 1.d0) then
        t2 = sqrt(-2.d0 * log(t1) / t1)
        t3 = (x1 * t2)
        t4 = (x2 * t2)
        l = max(abs(t3), abs(t4))
        q(l) = q(l) + 1.d0
        sx = sx + t3
        sy = sy + t4
    endif
  140  continue
if (timers_enabled) call timer_stop(2)

150  continue
<table>
<thead>
<tr>
<th>NAS Benchmark</th>
<th>Candidate Instructions</th>
<th>Configurations Tested</th>
<th>% Dynamic Replaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>bt.A</td>
<td>6,262</td>
<td>4,000</td>
<td>78.6</td>
</tr>
<tr>
<td>cg.A</td>
<td>956</td>
<td>255</td>
<td>5.6</td>
</tr>
<tr>
<td>ep.A</td>
<td>423</td>
<td>114</td>
<td>45.5</td>
</tr>
<tr>
<td>ft.A</td>
<td>426</td>
<td>74</td>
<td>0.2</td>
</tr>
<tr>
<td>lu.A</td>
<td>6,014</td>
<td>3,057</td>
<td>57.4</td>
</tr>
<tr>
<td>mg.A</td>
<td>1,393</td>
<td>437</td>
<td>36.6</td>
</tr>
<tr>
<td>sp.A</td>
<td>4,507</td>
<td>4,920</td>
<td>30.5</td>
</tr>
</tbody>
</table>
Issues

• High overhead
  – Must check and (possibly) convert operands before each instruction

• Lengthy search process
  – Search space is exponential wrt. instruction count

• Coarse-grained analysis
  – Binary decision: single or double
CRAFT (2016)

- Reduced-precision analysis
  - Simulate conservatively via bit-mask truncation
  - Report min output precision for each instruction
  - Finer-grained analysis and lower overhead
CRAFT (2016)

- Scalability via heuristic search
  - Focus on most-executed instructions
  - Analysis time vs. benefit tradeoff

- >5.0% - 4:66
- >1.0% - 5:93
- >0.5% - 9:45
- >0.1% - 15:45
- >0.05% - 23:60
- Full - 28:71
Issue

• Only considers precision reduction
  – No higher precision or arbitrary-precision
  – No alternative representations
  – No dynamic tracking of error
SHVAL (2016)

- Generic floating-point shadow value analysis
  - Maintain “shadow” value for every memory location
  - Execute shadow operations for all computation
  - Shadow type is parameterized (native, MPFR, Unum, Posit, etc.)
  - Pintool: less overhead than similar frameworks like Valgrind

```c
double sum = 0.0;
for (int i = 0; i < 10; i++) {
    sum += 0.1;
}
printf("\%25.2f\n", sum);
```

Fig. 3. Sample C program

Original machine code:

```assembly
pxor xmm0, xmm0
mov  eax, 10
movsd xmm1, 0x400628
loop:
    sub  eax, 1
    addsd xmm0, xmm1
    jne  loop
movsd 0x8(rsp), xmm0
```

Inserted shadow code:

```assembly
(set to 0.0) xmm[0] = convert(0.0)
(load 0.1) xmm[1] = convert(+(0x400628))
(increment) xmm[0] += xmm[1]
(store sum) mem[rsp+0x8] = xmm[0]
```

Fig. 4. Compiled assembly of program from Figure 3

<table>
<thead>
<tr>
<th>Shadow Value Type</th>
<th>Exp Size</th>
<th>Frac Size</th>
<th>Final Shadow Value</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-bit (native single)</td>
<td>8</td>
<td>23</td>
<td>1.000000</td>
<td>1.19e-07</td>
</tr>
<tr>
<td>64-bit (native double)</td>
<td>11</td>
<td>52</td>
<td>1.0000000000000000000</td>
<td>0</td>
</tr>
<tr>
<td>128-bit GNU MPFR</td>
<td>15</td>
<td>112</td>
<td>1.00000000000000000005551e+00</td>
<td>1.11e-16</td>
</tr>
<tr>
<td>Unum (3,2)</td>
<td>8</td>
<td>4</td>
<td>(0.9375, 1.1875)</td>
<td>0.059</td>
</tr>
<tr>
<td>Unum (3,4)</td>
<td>8</td>
<td>16</td>
<td>(0.9999847412109375, 1.0000457763671875)</td>
<td>1.53e-05</td>
</tr>
<tr>
<td>Unum (4,6)</td>
<td>16</td>
<td>64</td>
<td>1.000000000000000000005551...182</td>
<td>1.11e-16</td>
</tr>
</tbody>
</table>

TABLE I
ANALYSIS RESULTS ON SAMPLE PROGRAM
SHVAL (ongoing)

• Single precision shadow values
  – Trace execution and build data flow graph
  – Color nodes by error w.r.t. original double precision values
  – Highlights high-error regions
  – Inherent scaling issues

![Diagram of Gaussian elimination example]
Issue

• No source-level mixed precision
  – Difficult to translate instruction-level analysis results to source-level transformations
  – Some users might be satisfied with opaque compiler-based optimization, but most HPC users want to know what changed!
CRAFT (2013)

• Memory-based replacement analysis
  – Leave computation intact but round outputs
  – Aggregate instructions that modify same variable
  – Found several valid variable-level replacements

<table>
<thead>
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<th>Candidate Operands</th>
<th>Configurations Tested</th>
<th>% Executions Replaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>bt.A</td>
<td>2,342</td>
<td>300</td>
<td>97.0</td>
</tr>
<tr>
<td>cg.A</td>
<td>287</td>
<td>68</td>
<td>71.3</td>
</tr>
<tr>
<td>ep.A</td>
<td>236</td>
<td>59</td>
<td>37.9</td>
</tr>
<tr>
<td>ft.A</td>
<td>466</td>
<td>108</td>
<td>46.2</td>
</tr>
<tr>
<td>lu.A</td>
<td>1,742</td>
<td>104</td>
<td>99.9</td>
</tr>
<tr>
<td>mg.A</td>
<td>597</td>
<td>153</td>
<td>83.4</td>
</tr>
<tr>
<td>sp.A</td>
<td>1,525</td>
<td>1,094</td>
<td>88.9</td>
</tr>
</tbody>
</table>
• Single-vs-double shadow value analysis
  – Aggregate error by instruction or memory location over time

• Computer vision case study (Apriltags)
  – 1.7x speedup on average with only 4% error
  – 40% energy savings in embedded experiments

Fig. 1. Error trace per memory location. A darker pixel indicates higher error.
Issues

• Each instruction or variable is tested in isolation
  – Union of valid replacements is often invalid

• Cannot ensure speedup
  – Instrumentation overhead
  – Added casts to convert data between regions
  – Lack of vectorization and data packing
CRAFT (ongoing)

- Variable-centric mixed precision analysis
  - Use TypeForge (an AST-level type conversion tool) for source-to-source mixed precision

- Search for best speedup
  - Run full compiler backend w/ optimizations
  - Report fastest configuration that passes verification

```c
double sum = 0.0;
void sum2pi_x()
{
    double tmp;
double acc;
int i, j;

    [...] 
}

double sum = 0.0;
void sum2pi_x()
{
    float tmp;
float acc;
int i;
int j;

    [...] 
}```
Related Work

- CRAFT/SHVAL, Precimoniou [Rubio’13], GPUMixer [Laguna’19], etc.
  - Very **practical**
  - Widely-used tool frameworks (Dyninst, Pin, LLVM)
  - Few (or no) formal guarantees
  - Tested on HPC benchmarks on Linux/x86

- Daisy [Darulova’18], FPTuner [Chiang’17], etc.
  - Very **rigorous**
  - Custom input formats
  - Provable error bounds for given input range
  - Impractical for HPC benchmarks
ADAPT (2018)

- Automatic backwards error analysis
  - Obtain gradients via reverse-mode algorithmic differentiation (CoDiPack or TAPENADE)
  - Calculate error contribution of intermediate results
  - Aggregate by program variable
  - Greedy algorithm builds mixed-precision allocation

Credit: Harshitha Menon (gopalakrishn1@llnl.gov)
Original C Code

```c
#include <iostream>

double sum = 0.0;
double inc = 0.1;

double do_sum() {
    int i;
    for (i = 0; i < 1000; i++) {
        sum += inc;
    }
    return sum;
}

int main() {
    do_sum();
    cout << sum << endl;

    return 0;
}
```

AD Instrumented Code

```c
#include <iostream>
#include <adapt.h>
#include <adapt-impl.cpp>

AD_real sum = 0.0;
AD_real inc = 0.1;

AD_real do_sum() {
    int i;
    for (i = 0; i < 1000; i++) {
        sum += inc;
    }
    return sum;
}

int main() {
    AD_begin();
    AD_independent(inc, "inc");
    do_sum();
    cout << AD_value(sum) << endl;

    AD_dependent(sum, "sum", 8);
    AD_report();
    return 0;
}
```

- AD Libraries
- Type Changes
- Initialization
- Output
• Used ADAPT on LULESH benchmark to help develop a mixed-precision CUDA version

• Achieved speedup of 20% within original error threshold on NVIDIA GK110 GPU
FloatSmith (ongoing)

- Mixed-precision search via CRAFT
- Source-to-source translation via TypeForge
- Optionally, use TypeForge-automated ADAPT analysis to narrow search and provide more rigorous guarantees
FloatSmith (ongoing)

- Guided mode (Q&A)
- Batch mode (command-line parameters)
- Dockerfile provided
- Can offload configuration testing to a cluster

```
floatsmith -B --run "./demo"
```

declare double p = 1.00000003;
declare double l = 0.00000003;
declare double o;

```
int main() {
  o = p + l;
  // should print 1.00000006
  printf("%.8f", (double)o);
  return 0;
}
```

declare double p = 1.00000003;
declare float l = 0.00000003;
declare double o;

```
int main() {
  o = p + l;
  // should print 1.00000006
  printf("%.8f", (double)o);
  return 0;
}
```
FPHPC (ongoing)

• Benchmark suite aimed at facilitating scale-up for mixed-precision analysis tools
  – “Middle ground” between real-valued expressions and full applications
  – Currently looking for good case studies
Future Work

• (Better) OpenMP/MPI support
• (Better) GPU and FPGA support
• Model-based performance prediction
• Dynamic runtime precision tuning
• Ensemble floating-point analysis
Summary

• Automated mixed precision is possible
  – Practicality vs. rigor tradeoff
• Multiple active projects
  – Various goals and approaches
  – All target HPC applications
• Many avenues for future research
Papers

- **CRAFT**

- **SHVAL**

- **ADAPT**
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github.com/crafthpc
github.com/llnl/adapt-fp
tinyurl.com/fpanalysis

Contact me:
lam2mo@jmu.edu