EECS 583 – Class 9
Classic + ILP Optimization

University of Michigan

February 6, 2023

Announcements & Reading Material

- Hopefully everyone is making some progress on HW 2
  - Due Feb 15
- Today's class
  - "Compiler Code Transformations for Superscalar-Based High-Performance Systems," S. Mahlke, W. Chen, J. Gyllenhaal, W. Hwu, P, Chang, and T. Kiyohara, *Proceedings of Supercomputing '92*, Nov. 1992, pp. 808-817
- Next class (code generation)
  - "Machine Description Driven Compilers for EPIC Processors", B. Rau, V. Kathail, and S. Aditya, HP Technical Report, HPL-98-40, 1998. (long paper but informative)

Course Project – Time to Start Thinking About This

- Mission statement: Design and implement something "interesting" in a compiler
  - » LLVM preferred, but others are fine
  - » Groups of 3-4 people (other group sizes are possible in some cases)
  - » Extend existing research paper or go out on your own
- Topic areas (Not in any priority order)
  - » Automatic parallelization/SIMDization
  - » High level synthesis/FPGAs
  - » Approximate computing
  - » Memory system optimization
  - » Reliability
  - » Energy
  - » Security
  - » Dynamic optimization
  - » Machine learning for compilers
  - » Optimizing for GPUs

Course Projects – Timetable

- Now - Start thinking about potential topics, identify group members
  - Use piazza to recruit group members
- Mar 6-10: Project proposal discussions, No class Mar 6/8 (Previous week is Spring Break),– Regular class resumes Mon Mar 13
  - Aditya and I will meet with each group virtually for 5-10 mins, slot signups the week before Feb 20-24
  - Ideas/proposal discussed at meeting – don't come into the meeting with too many ideas (1-2 only)
  - Short written proposal (a paragraph plus 1-2 references) due Mon, Mar 13 from each group, submit via email
- Mar 20 – End of semester: Research presentations (details later)
  - Each group presents a research paper related to their project (15 mins)
- Late Mar - Optional quick discussion with groups on progress
- Apr 17-21: Project demos
  - Each group, 15 min slot - Presentation/Demo/whatever you like
  - Turn in short report on your project

Sample Project Ideas (Traditional)

- Memory system
  - Cache profiler for LLVM IR – miss rates, stride determination
  - Data cache prefetching, cache bypassing, scratch pad memories
  - Data layout for improved cache behavior
  - Advanced loads – move up to hide latency
- Control/Dataflow optimization
  - Superblock formation
  - Make an LLVM optimization smarter with profile data
  - Implement optimization not in LLVM
- Reliability
  - AVF profiling, vulnerability analysis
  - Selective code duplication for soft error protection
  - Low-cost fault detection and/or recovery
  - Efficient soft error protection on GPUs/SIMD

Sample Project Ideas (Traditional cont)

- Energy
  - Minimizing instruction bit flips
  - Deactivate parts of processor (FUs, registers, cache)
  - Use different processors (e.g., big.LITTLE)
- Security/Safety
  - Efficient taint/information flow tracking
  - Automatic mitigation methods – obfuscation for side channels
  - Preventing control flow exploits
  - Rule compliance checking (driving rules for AV software)
  - Run-time safety verification
- Dealing with pointers
  - Memory dependence analysis – try to improve on LLVM
  - Using dependence speculation for optimization or code reordering

Sample Project Ideas (Parallelism)

- Optimizing for GPUs
  - Dumb OpenCL/CUDA → smart OpenCL/CUDA – selection of threads/blocks and managing on-chip memory
  - Reducing uncoalesced memory accesses – measurement of uncoalesced accesses, code restructuring to reduce these
  - Matlab → CUDA/OpenCL
  - Kernel partitioning, data partitioning across multiple GPUs
- Parallelization/SIMDization
  - DOALL loop parallelization, dependence breaking transformations
  - DSWP parallelization
  - Access-execute program decomposition
  - Automatic SIMDization, Superword level parallelism

More Project Ideas

- Dynamic optimization (Dynamo, LLVM, Dalvik VM)
  - Run-time DOALL loop parallelization
  - Run-time program analysis for reliability/security
  - Run-time profiling tools (cache, memory dependence, etc.)
- Binary optimizer
  - Arm binary to LLVM IR, de-register allocation
- High level synthesis
  - Custom instructions - finding most common instruction patterns, constrained by inputs/outputs
  - Int/FP precision analysis, Float to fixed point
  - Custom data path synthesis
  - Customized memory systems (e.g., sparse data structs)

And Yet a Few More

- Approximate computing
  - New approximation optimizations (lookup tables, loop perforation, tiling)
  - Impact of local approximation on global program outcome
  - Program distillation - create a subset program with equivalent memory/branch behavior
- Machine learning for compilers
  - Using ML/search to guide optimizations (e.g., unroll factors)
  - Using ML/search to guide optimization choices (which optis/order)
  - Be careful with low compiler content!!

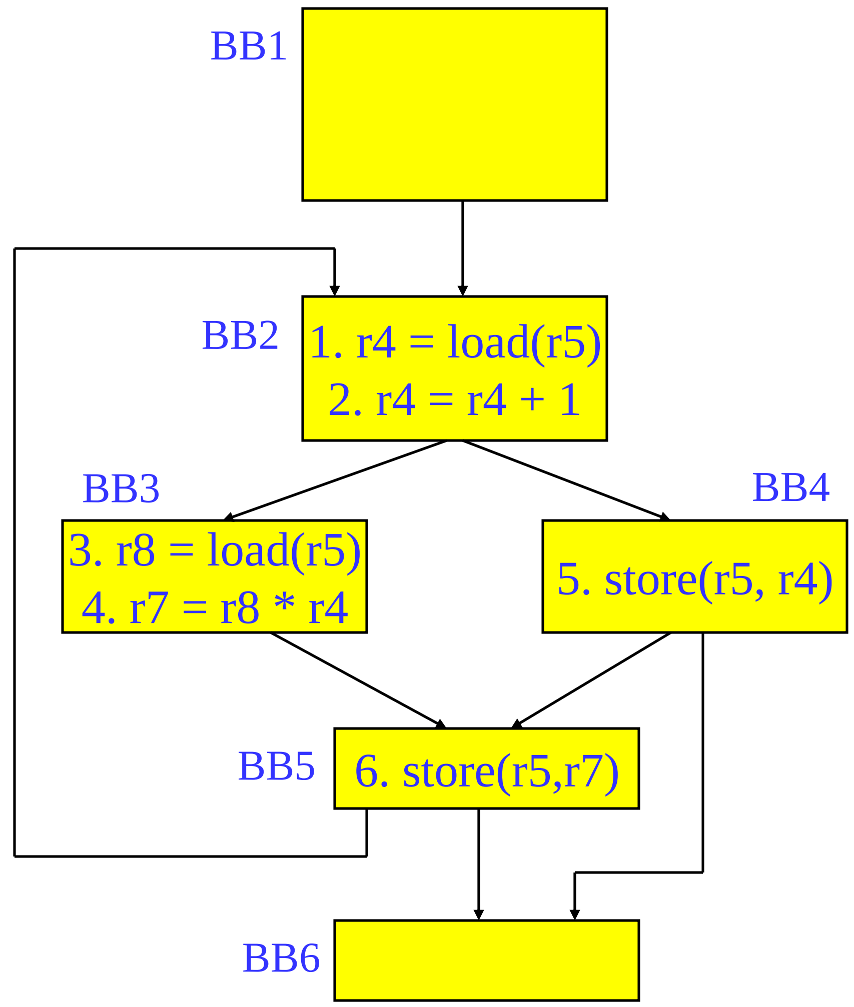
- Remember, don't be constrained by my suggestions, you can pick other topics!

Back to Code Optimization

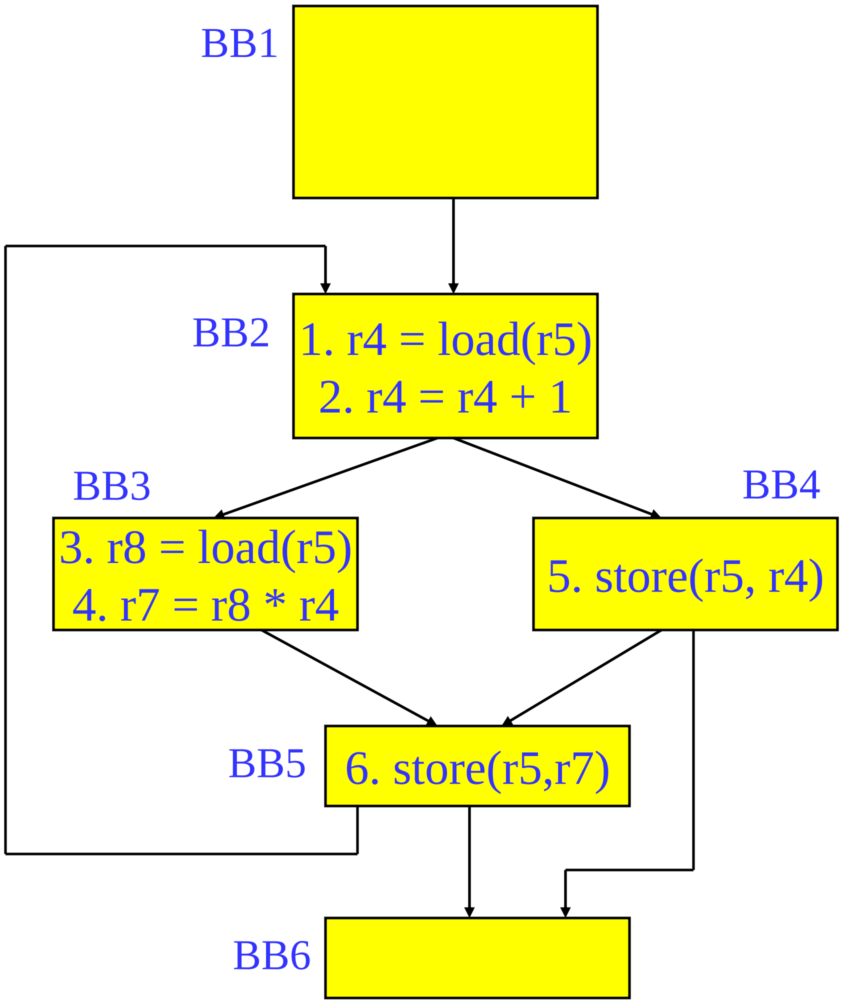
- Classical (machine independent, done at IR level)
  - Reducing operation count (redundancy elimination)
  - Simplifying operations
  - Generally good for any kind of machine
- We went through
  - Dead code elimination
  - Constant propagation
  - Constant folding
  - Copy propagation
  - CSE
  - LICM

Global Variable Migration

- Assign a global variable temporarily to a register for the duration of the loop
  - Load in preheader
  - Store at exit points
- Rules
  - X is a load or store
  - address(X) not modified in the loop
  - if X not executed on every iteration, then X must provably not cause an exception
  - All memory ops in loop whose address can equal address(X) must always have the same address as X

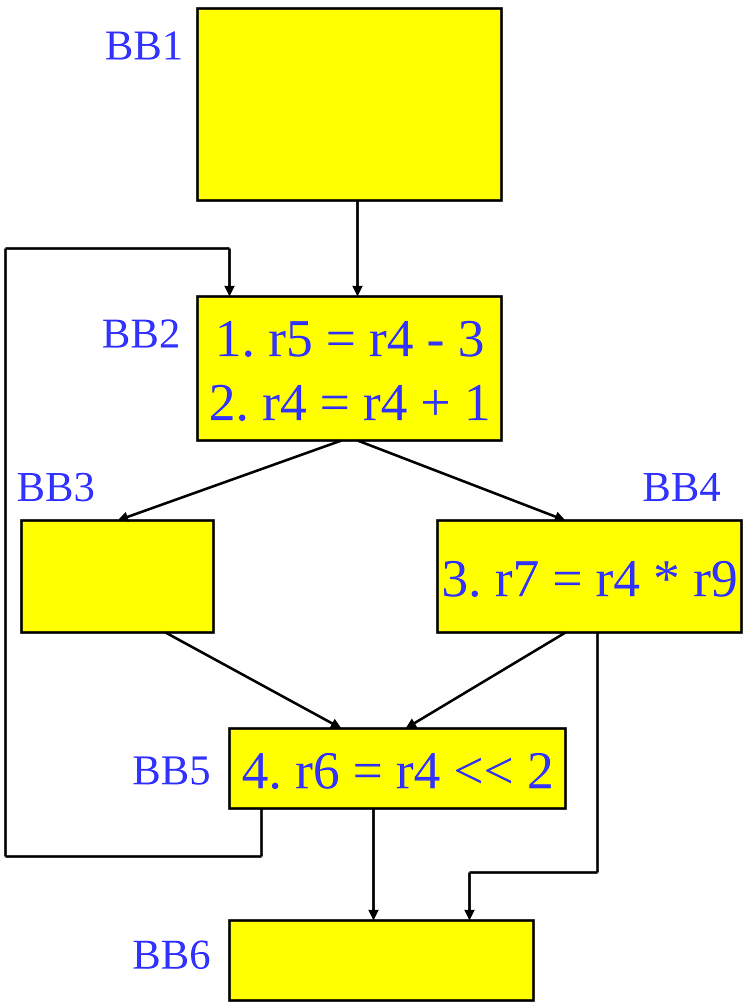


Global Variable Migration Example



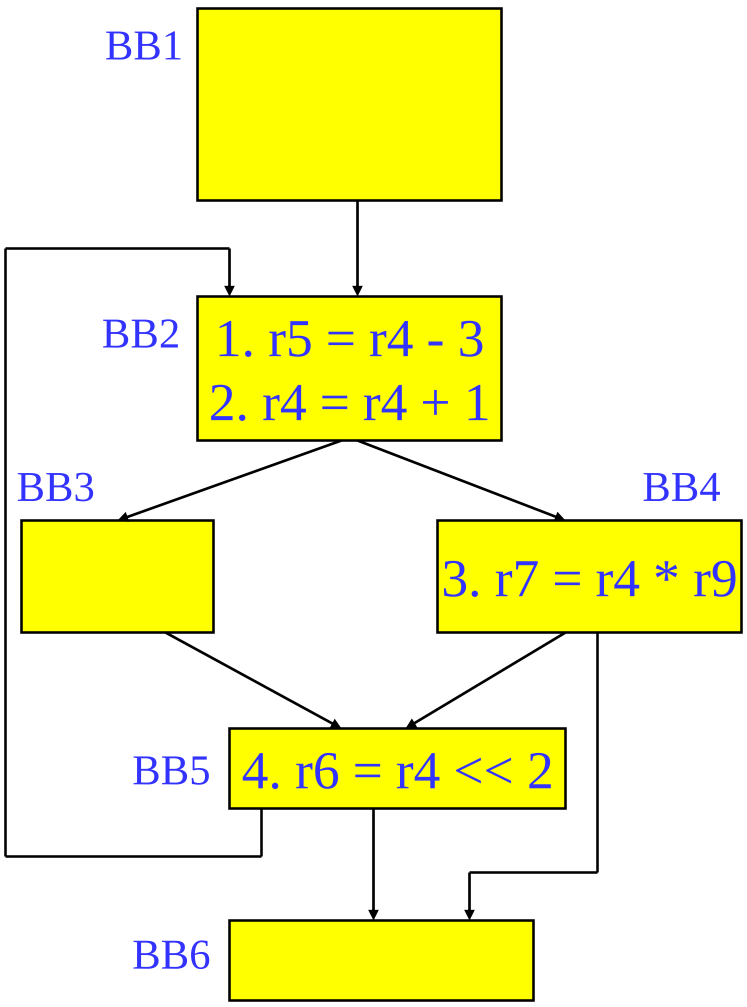
Induction Variable Strength Reduction

- Create basic induction variables from derived induction variables
- Induction variable
  - » BIV (i++)
    - 0,1,2,3,4,...
  - » DIV (j = i * 4)
    - 0, 4, 8, 12, 16, ...
  - » DIV can be converted into a BIV that is incremented by 4
- Issues
  - » Initial and increment vals
  - » Where to place increments

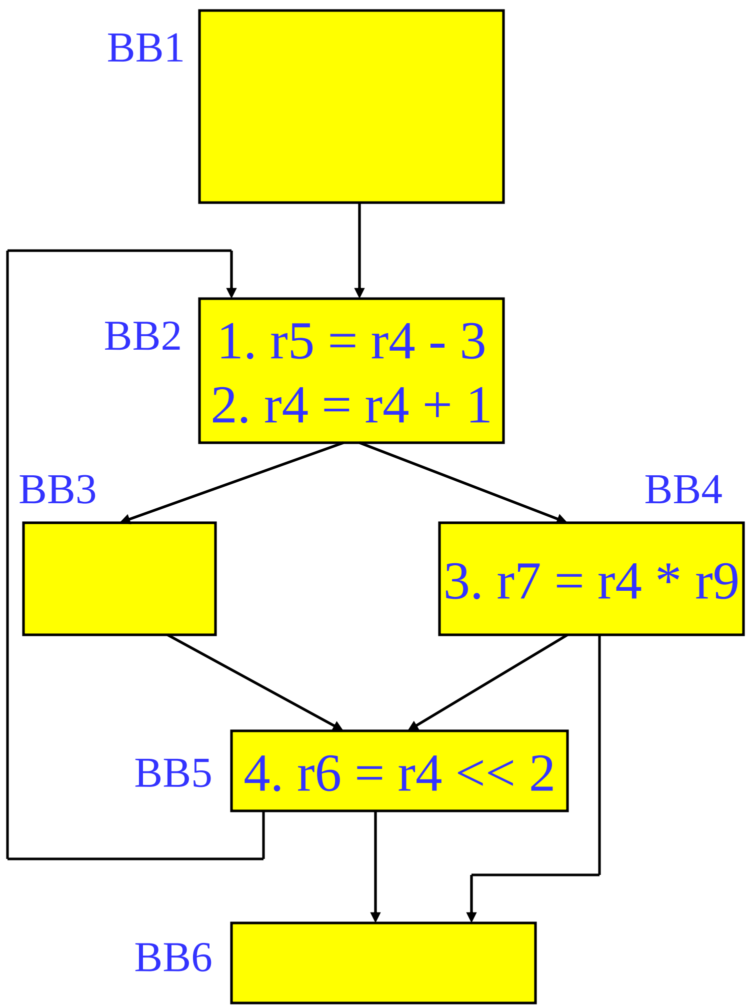


Induction Variable Strength Reduction (2)

- Rules
  - X is a *, <<, + or – operation
  - src1(X) is a basic ind var
  - src2(X) is invariant
  - No other ops modify dest(X)
  - dest(X) != src(X) for all srcs
  - dest(X) is a register
- Transformation
  - Insert the following into the preheader
    - new_reg = RHS(X)
  - If opcode(X) is not add/sub, insert to the bottom of the preheader
    - new_inc = inc(src1(X)) opcode(X) src2(X)
  - else
    - new_inc = inc(src1(X))
  - Insert the following at each update of src1(X)
    - new_reg += new_inc
  - Change X → dest(X) = new_reg



Induction Variable Strength Reduction - Example



Class Problem

Optimize this applying induction var str reduction

BB1
```
1. r1 = 0
2. r2 = 0
```

BB2
```
3. r5 = r5 + 1
4. r11 = r5 * 2
5. r10 = r11 + 2
6. r12 = load (r10+0)
7. r9 = r1 << 1
8. r4 = r9 - 10
9. r3 = load(r4+4)
10. r3 = r3 + 1
11. store(r4+0, r3)
12. r7 = r3 << 2
13. r6 = load(r7+0)
14. r13 = r2 - 1
15. r1 = r1 + 1
16. r2 = r2 + 1
```

BB3
r13, r12, r6, r10
liveout

Class Problem Solution

Optimize this applying induction var str reduction

```
r1 = 0
r2 = 0
```

```
r5 = r5 + 1
r11 = r5 * 2
r10 = r11 + 2
r12 = load (r10+0)
r9 = r1 << 1
r4 = r9 - 10
r3 = load(r4+4)
r3 = r3 + 1
store(r4+0, r3)
r7 = r3 << 2
r6 = load(r7+0)
r13 = r2 - 1
r1 = r1 + 1
r2 = r2 + 1
```

```
r13, r12, r6, r10
liveout
```

→

```
r1 = 0
r2 = 0
r111 = r5 * 2
r109 = r1 << 1
r113 = r2 -1
```

```
r5 = r5 + 1
r111 = r111 + 2
r11 = r111
r10 = r11 + 2
r12 = load (r10+0)
r9 = r109
r4 = r9 - 10
r3 = load(r4+4)
r3 = r3 + 1
store(r4+0, r3)
r7 = r3 << 2
r6 = load(r7+0)
r13 = r113
r1 = r1 + 1
r109 = r109 + 2
r2 = r2 + 1
r113 = r113 + 1
```

```
r13, r12, r6, r10
liveout
```

Note, after copy propagation, r10 and r4 can be strength reduced as well.

ILP Optimization

- Traditional optimizations
  - Redundancy elimination
  - Reducing operation count
- ILP (instruction-level parallelism) optimizations
  - Increase the amount of parallelism and the ability to overlap operations
  - Operation count is secondary, often trade parallelism for extra instructions (avoid code explosion)
- ILP increased by breaking dependences
  - True or flow = read after write dependence
  - False or (anti/output) = write after read, write after write

Back Substitution

- Generation of expressions by compiler frontends is very sequential
  - » Account for operator precedence
  - » Apply left-to-right within same precedence
- Back substitution
  - » Create larger expressions
    - Iteratively substitute RHS expression for LHS variable
  - » Note – may correspond to multiple source statements
  - » Enable subsequent optis
- Optimization
  - » Re-compute expression in a more favorable manner

y = a + b + c – d + e – f;

1. r9 = r1 + r2
2. r10 = r9 + r3
3. r11 = r10 - r4
4. r12 = r11 + r5
5. r13 = r12 – r6

Subs r12:
r13 = r11 + r5 – r6
Subs r11:
r13 = r10 – r4 + r5 – r6
Subs r10
r13 = r9 + r3 – r4 + r5 – r6
Subs r9
r13 = r1 + r2 + r3 – r4 + r5 – r6

Tree Height Reduction

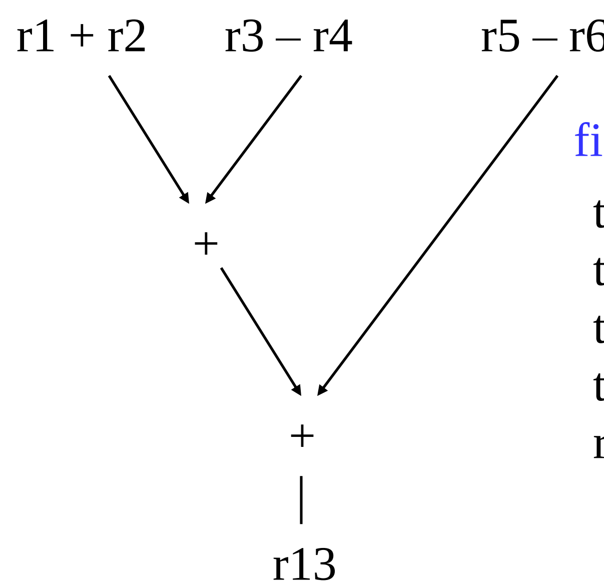
- Re-compute expression as a balanced binary tree
  - Obey precedence rules
  - Essentially re-parenthesize
  - Combine literals if possible
- Effects
  - Height reduced (n terms)
    - n-1 (assuming unit latency)
    - ceil(log2(n))
  - Number of operations remains constant
  - Cost
    - Temporary registers “live” longer
  - Watch out for
    - Always ok for integer arithmetic
    - Floating-point – may not be!!

original:

r9 = r1 + r2
r10 = r9 + r3
r11 = r10 - r4
r12 = r11 + r5
r13 = r12 – r6

after back subs:

r13 = r1 + r2 + r3 – r4 + r5 – r6



final code:

t1 = r1 + r2
t2 = r3 – r4
t3 = r5 – r6
t4 = t1 + t2
r13 = t4 + t3

Class Problem

Assume: + = 1, * = 3

operand arrival times	0	0	0	1	2	0
	r1	r2	r3	r4	r5	r6

1. r10 = r1 * r2
2. r11 = r10 + r3
3. r12 = r11 + r4
4. r13 = r12 – r5
5. r14 = r13 + r6

Back susbstitute

Re-express in tree-height reduced form

<u>Account for latency and arrival times</u>

Loop Unrolling

```
for (i=x; i< 100; i++) {
    sum += a[i]*b[i];
}
```

```
loop:   r1 = load(r2)
        r3 = load(r4)
        r5 = r1 * r3
        r6 = r6 + r5
        r2 = r2 + 4
        r4 = r4 + 4
        if (r4 < 400) goto loop
```

Unroll = replicate loop body n-1 times.

Hope to enable overlap of operation execution from different iterations

unroll 3 times

```
loop:   r1 = load(r2)
        r3 = load(r4)
        r5 = r1 * r3
        r6 = r6 + r5
iter1   r2 = r2 + 4
        r4 = r4 + 4
        if (r4 >= 400) goto exit
        ----------------------------
        r1 = load(r2)
        r3 = load(r4)
        r5 = r1 * r3
iter2   r6 = r6 + r5
        r2 = r2 + 4
        r4 = r4 + 4
        if (r4 >= 400) goto exit
        ----------------------------
        r1 = load(r2)
        r3 = load(r4)
iter3   r5 = r1 * r3
        r6 = r6 + r5
        r2 = r2 + 4
        r4 = r4 + 4
        if (r4 < 400) goto loop
exit:
```

Smarter Loop Unrolling with Known Trip Count

Want to remove early exit branches

Trip count = 400/4 = 100

```
      r4 = 0
loop: r1 = load(r2)
      r3 = load(r4)
      r5 = r1 * r3
      r6 = r6 + r5
      r2 = r2 + 4
      r4 = r4 + 4
      if (r4 < 400) goto loop
```

unroll multiple of trip count

```
loop:  r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter1  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
       ---------------------
       r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter2  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
       ---------------------
       r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter3  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
       ---------------------
       r1 = load(r2)
       r3 = load(r4)
iter4  r5 = r1 * r3
       r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
       if (r4 < 400) goto loop
exit:
```

What if the Trip Count is not Statically Known?

```
      r4 = ??
loop: r1 = load(r2)
      r3 = load(r4)
      r5 = r1 * r3
      r6 = r6 + r5
      r2 = r2 + 4
      r4 = r4 + 4
      if (r4 < 400) goto loop
```

Create a preloop to ensure trip count of unrolled loop is a multiple of the unroll factor

```
preloop  for (i=0; i< ((400-r4)/4)%3; i++) {
            sum += a[i]*b[i];
         }

loop:    r1 = load(r2)
         r3 = load(r4)
iter1    r5 = r1 * r3
         r6 = r6 + r5
         r2 = r2 + 4
         r4 = r4 + 4
       -------------------
         r1 = load(r2)
         r3 = load(r4)
iter2    r5 = r1 * r3
         r6 = r6 + r5
         r2 = r2 + 4
         r4 = r4 + 4
       -------------------
         r1 = load(r2)
         r3 = load(r4)
         r5 = r1 * r3
iter3    r6 = r6 + r5
         r2 = r2 + 4
         r4 = r4 + 4
         if (r4 < 400) goto loop
exit:
```

Unrolling Not Enough for Overlapping Iterations: Register Renaming

```
loop:  r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter1  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
      --------------------
       r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter2  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
      --------------------
       r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter3  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
       if (r4 < 400) goto loop
```

```
loop:  r1 = load(r2)
       r3 = load(r4)
       r5 = r1 * r3
iter1  r6 = r6 + r5
       r2 = r2 + 4
       r4 = r4 + 4
      --------------------
       r11 = load(r2)
       r13 = load(r4)
       r15 = r11 * r13
iter2  r6 = r6 + r15
       r2 = r2 + 4
       r4 = r4 + 4
      --------------------
       r21 = load(r2)
       r23 = load(r4)
       r25 = r21 * r23
iter3  r6 = r6 + r25
       r2 = r2 + 4
       r4 = r4 + 4
       if (r4 < 400) goto loop
```

Register Renaming is Not Enough!

```
loop: r1 = load(r2)
      r3 = load(r4)
      r5 = r1 * r3
iter1 r6 = r6 + r5
      r2 = r2 + 4
      r4 = r4 + 4
    --------------------
      r11 = load(r2)
      r13 = load(r4)
      r15 = r11 * r13
iter2 r6 = r6 + r15
      r2 = r2 + 4
      r4 = r4 + 4
    --------------------
      r21 = load(r2)
      r23 = load(r4)
      r25 = r21 * r23
iter3 r6 = r6 + r25
      r2 = r2 + 4
      r4 = r4 + 4
      if (r4 < 400) goto loop
```

- Still not much overlap possible
- Problems
  - r2, r4, r6 sequentialize the iterations
  - Need to rename these
- 2 specialized renaming optis
  - Accumulator variable expansion (r6)
  - Induction variable expansion (r2, r4)

Accumulator Variable Expansion

```
         r16 = r26 = 0
loop:    r1 = load(r2)
         r3 = load(r4)
         r5 = r1 * r3
iter1    r6 = r6 + r5
         r2 = r2 + 4
         r4 = r4 + 4
        --------------------
         r11 = load(r2)
         r13 = load(r4)
         r15 = r11 * r13
iter2    r16 = r16 + r15
         r2 = r2 + 4
         r4 = r4 + 4
        --------------------
         r21 = load(r2)
         r23 = load(r4)
         r25 = r21 * r23
iter3    r26 = r26 + r25
         r2 = r2 + 4
         r4 = r4 + 4
         if (r4 < 400) goto loop
exit:    r6 = r6 + r16 + r26
```

- Accumulator variable
  - x = x + y or x = x – y
  - where y is loop variant!!
- Create n-1 temporary accumulators
- Each iteration targets a different accumulator
- Sum up the accumulator variables at the end
- May not be safe for floating-point values

Induction Variable Expansion

```
        r12 = r2 + 4, r22 = r2 + 8
        r14 = r4 + 4, r24 = r4 + 8
        r16 = r26 = 0
loop:   r1 = load(r2)
        r3 = load(r4)
        r5 = r1 * r3
iter1   r6 = r6 + r5
        r2 = r2 + 12
        r4 = r4 + 12
       ---------------------
        r11 = load(r12)
        r13 = load(r14)
        r15 = r11 * r13
iter2   r16 = r16 + r15
        r12 = r12 + 12
        r14 = r14 + 12
       ---------------------
        r21 = load(r22)
        r23 = load(r24)
        r25 = r21 * r23
iter3   r26 = r26 + r25
        r22 = r22 + 12
        r24 = r24 + 12
        if (r4 < 400) goto loop
exit:   r6 = r6 + r16 + r26
```

- Induction variable
  - x = x + y or x = x – y
  - where y is loop invariant!!
- Create n-1 additional induction variables
- Each iteration uses and modifies a different induction variable
- Initialize induction variables to init, init+step, init+2*step, etc.
- Step increased to n*original step
- Now iterations are completely independent !!

Better Induction Variable Expansion

```
          r16 = r26 = 0
loop:     r1 = load(r2)
          r3 = load(r4)
          r5 = r1 * r3
iter1     r6 = r6 + r5

        --------------------
          r11 = load(r2+4)
          r13 = load(r4+4)
          r15 = r11 * r13
iter2     r16 = r16 + r15

        --------------------
          r21 = load(r2+8)
          r23 = load(r4+8)
          r25 = r21 * r23
iter3     r26 = r26 + r25
          r2 = r2 + 12
          r4 = r4 + 12
          if (r4 < 400) goto loop
exit:     r6 = r6 + r16 + r26
```

- With base+displacement addressing, often don't need additional induction variables
  - » Just change offsets in each iterations to reflect step
  - » Change final increments to n * original step

Homework Problem

loop:
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
if (r2 < 400) goto loop

Optimize the unrolled loop

Renaming
Tree height reduction
Ind/Acc expansion

loop:
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
if (r2 < 400) goto loop

Homework Problem - Answer

```
loop:
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
if (r2 < 400) goto loop
```

Optimize the unrolled loop

Renaming
Tree height reduction
Ind/Acc expansion

```
loop:
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
r1 = load(r2)
r5 = r6 + 3
r6 = r5 + r1
r2 = r2 + 4
if (r2 < 400)
   goto loop
```

```
loop:
  r1 = load(r2)
  r5 = r1 + 3
  r6 = r6 + r5
  r2 = r2 + 4
  r11 = load(r2)
  r15 = r11 + 3
  r6 = r6 + r15
  r2 = r2 + 4
  r21 = load(r2)
  r25 = r21 + 3
  r6 = r6 + r25
  r2 = r2 + 4
  if (r2 < 400)
     goto loop
```

after renaming and tree height reduction

```
r16 = r26 = 0
loop:
 r1 = load(r2)
 r5 = r1 + 3
 r6 = r6 + r5
 r11 = load(r2+4)
 r15 = r11 + 3
 r16 = r16 + r15
 r21 = load(r2+8)
 r25 = r21 + 3
 r26 = r26 + r25
 r2 = r2 + 12
 if (r2 < 400)
    goto loop
 r6 = r6 + r16
 r6 = r6 + r26
```

after acc and ind expansion