COMP 512
Rice University
Spring 2015

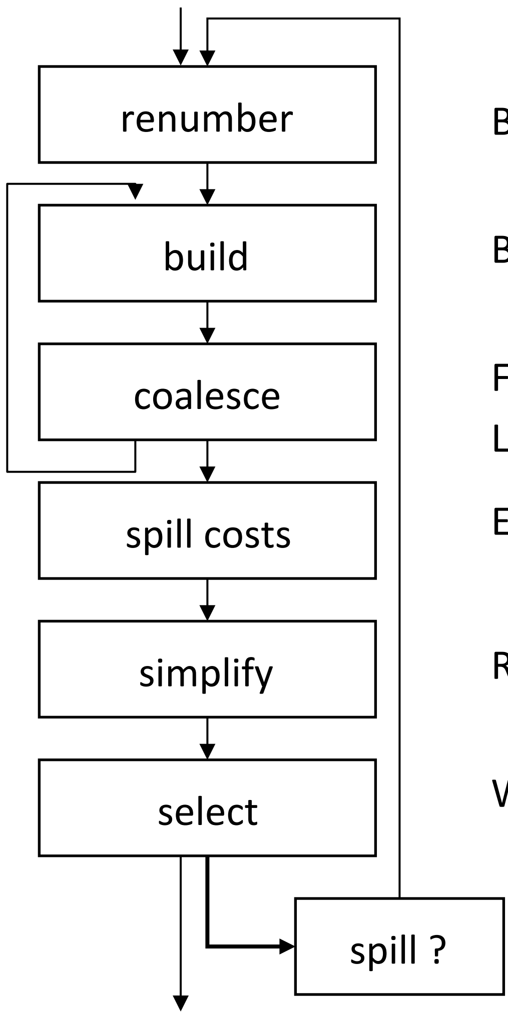
Register Allocation via Graph Coloring

Beyond Chaitin Briggs

Citation numbers refer to entries in the EaC2e bibliography.

From Last Lecture

Chaitin-Briggs Allocator (Optimistic Coloring)



Build SSA, build live ranges, rename

Build the interference graph

Fold unneeded copies

$LR_x \rightarrow LR_y$, and $<LR_x,LR_y> \notin G_I \Rightarrow$ combine LR_x & LR_y

Estimate cost for spilling
each live range

Remove nodes from the graph

while N is non-empty
  if $\exists$ n with $n^\circ < k$ then
    push n onto stack
  else pick n to spill
    push n onto stack
  remove n from G_I

While stack is non-empty
  pop n, insert n into G_I, & try to color it

Spill uncolored definitions & uses

Briggs' algorithm

How do these allocators do?

Results are "pretty good"

- Simple procedures allocate without spills
- There is some room for improvement
  - ♦ Long blocks, regions of high pressure
  - ♦ Many implementation issues
- Many people have looked at improving Chaitin-Briggs

Better allocations

- Better coloring
- Softer coalescing
- Better spilling
- Spilling partial live ranges

Better implementations

- Faster graph construction
- Faster coalescing

Different approximate graphs

- Linear Scan allocation
- **SSA**-based allocation
- Koblenz-Callahan

Roadmap for Today's Lecture

More Detail

- Building the interference graph
- Coalescing, biased coloring, & limited lookahead

Improvements

- Better coloring
- Better spilling, including live-range splitting, partial live-range spilling, and rematerialization

Different Approximations

- Linear scan allocators
- **SSA**-based allocators
- Koblenz-Callahan Hierarchical Allocator

Building the Interference Graph

Need two representations

- Bit matrix
  - ♦ Fast test for specific interference
  - ♦ Need upper (lower) diagonal submatrix
  - ♦ Takes fair amount of space & time
- Adjacency lists
  - ♦ Fast iteration over neighbors
  - ♦ Needed to find colors, count degree
  - ♦ Must tightly bound space to make it practical

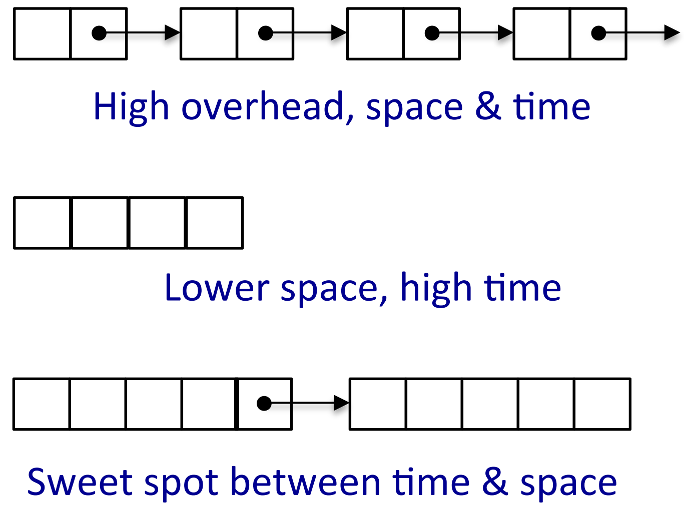
Both Chaitin & Briggs recommend two passes [73,74,75,49,51,52,56]

- First pass builds bit matrix and sizes adjacency vectors
- Second pass builds adjacency vectors into perfect-sized arrays

Building the Interference Graph

Split the graph into disjoint register classes [101]

- Separate **GPR**s from **FPR**s
  - ♦ Others may make sense (**CC**s, predicates)
- Graph is still n^2, but n is smaller
- In practice, **GPR/FPR** split is significant



Clique separators [175]

Build adjacency lists in a single pass [101]

- Block allocate adjacency lists (*30 edges per block*)
- Reduce amount of wasted space & pointer overhead
- Simple time-space tradeoff

Significance:

- 75% of space (Chaitin-Briggs) with one fewer pass [101]
- 70% of time (Chaitin-Briggs) for whole allocation [101]

Building the Interference Graph

Hash table implementation [75, 158]

- If graph is sparse, replace bit-matrix with hash table
  - ♦ Chaitin tried it and discarded the idea
  - ♦ George & Appel claim it beat the bit matrix in space & time

Our experience [101]

- Finding a good hash function takes care
  - ♦ Universal hash function from Cormen, Leiserson, & Rivest
  - ♦ Multiplicative hash function from Knuth
- Takes graphs with many thousands of **LR**s to overtake split bit-matrix implementation

Significance:

- 199% to 656% space versus Chaitin-Briggs [101]
- 124% to 4500% allocation time versus Chaitin-Briggs [101]

Coalescing

A Little More Detail On Coalescing In Chaitin-Briggs (See § 13.4.6 in EaC2e)

- Build the interference graph, *I*
  - ♦ For a copy, $LR_x \rightarrow LR_y$, add edges from LR_y to each node in LIVENOW except LR_x
- If $LR_x \rightarrow LR_y$, and $<LR_x,LR_y> \notin I$, then allocator can combine LR_x & Lr_y and delete the copy operation
  - ♦ Briggs showed examples where coalescing eliminated 1/3 of the live ranges
- Need to update *I*
  - ♦ In general, LR_{xy} interferes with the all of LR_x and LR_y's conflicts
  - ♦ To get best results, need a precise update, so we iterate build-coalesce

The dominant cost in a Chaitin-Briggs allocator is graph building [51]

- Circular problem: coalescing reduces number of live ranges, number of live ranges determines cost of building graph, coalescing needs graph, …
- See later slides on speeding up the allocator

1st interference graph is the biggest

Conservative Coalescing

Conservative coalescing avoids making the graph harder to color

Chaitin's scheme coalesces every copy that it can

- Coalescing *i* and *j* can create $ij° > \max(I°, j°)$
  - ♦ May make *ij* harder to color
  - ♦ In some contexts, this is important
- We can limit coalescing to conservative cases [55, 56]
  - ♦ Idea: Only create *ij* if it will get a color
  - ♦ Tempting to say that we need $ij° < k$, so *ij* is trivially colored
  - ♦ In fact, we need that *ij* has fewer than *k* neighbors of significant degree
- We can also bias the color selection [55,56]
  - ♦ If *i* and *j* are connected by a copy, try to pick the same color
  - ♦ If the other one is not yet colored, pick a color still open for it
  - ♦ Generalize to multiple copies (*but only immediate neighbors*)
  - ♦ "biased coloring with limited lookahead"

Might retrofit this more expensive test into Simplify …

Building on Conservative Coalescing

Iterated Coalescing [158]

- Use conservative coalescing, always
- If no trivially colored node remains, coalesce again
- Coalescing reduces degree in the graph
- Makes sense only if allocator uses conservative coalescing

Invented for Standard ML of New Jersey

- Long parameter lists, passed in registers
- Code shape adds many additional edges
- I think that they hit the known bug in "NeedLoad()" [Harvey, PhD thesis]
- Iterated coalescing cured their problem

Editorial Opinion

Conservative coalescing is oversold

- Designed to remove unproductive splits
  - ♦ Insert "special" copies & coalesce ones that don't help
  - ♦ Worked pretty well for that purpose
- Looks great on paper
  - ♦ Why coalesce if things get worse?
  - ♦ Conservative coalescing never makes things worse

In practice, Chaitin gets most coalesced LRs

- Briggs should get even more
- Don't be afraid to coalesce aggressively
  - ♦ With passive splitting & **IR** spilling, might even be better

See Max Hailperin, "Comparing conservative coalescing criteria," ACM TOPLAS 27(3), May 2005, pages 571-582.

Support for Editorial Opinion

Donghua Liu built a coloring allocator where he could adjust the value of *k*

- Roughly, a Chaitin-Briggs allocator in LLVM
- Distinguished between *k* in conservative coalescing & in coloring
- Distinguished between *k* in integer registers & floating-point registers
  - ♦ Gave him 4 distinct values of *k* to tune

Holding *k* for coloring fixed, found the best value of *k* for coalescing was around 39 to 42 on an Intel Nehalem processor (nominal 32 registers)

Donghua Liu, MS Thesis, Rice CS Dept.

Better Coloring

Several Authors Have Tried To Improve The Quality of Coloring

- Optimal coloring [Wilken]
  - ♦ Use backtracking to find minimal chromatic number
  - ♦ Took lots of compile-time
  - ♦ Found (some) better allocations

Done in GCC with a Chow allocator

- Random-walk coloring [Dietz]
  - ♦ Rather than spill, color remaining nodes in a random walk over the remaining graph
  - ♦ Did rather well on random graphs

No real basis to believe that it helps

Neither of these ideas has been widely used (*beyond the original authors*)

Unfortunately, some codes need more than *k* registers

- ♦ Better coloring will not help these codes
- ♦ Only helps when better coloring eliminates spills – a narrow range of codes

One Last Coalescing Idea: Faster Coalescing

The bit matrix requires an n^2 data structure

- We reduce *n* by including in the interference graph only lRs involved in copy operations
  - ♦ An analog of Briggs' semi-pruned SSA idea
  - ♦ Only include in the analysis things that can matter
  - ♦ Only works with "reckless" coalescing (*i.e., non conservative*)

Experience

- Informally, it runs in about 66% of the time of the coalescing with the full graph

Better Spilling

The Actual Performance Degradation Comes From Spilling

- Strongly suggests that we should look at better ways to spill
- If you want to reduce costs, you have to look where they are incurred
  - → *Register allocation version of Dillinger's observation*

What is wrong with Chaitin's spill methodology?

- It chooses values to spill based on the graph rather than the code
  - → Value that minimizes (Spill Cost/Degree) may not be live in region of high pressure
- Once it picks a value to spill, it spills that value everywhere
  - → *Could limit spilling to regions where demand for registers is greater than supply*
  - → *Could break spilled live ranges into pieces and try again* *(live-range splitting)*

Better Spilling

Some Proposed Improvements

- Clean spilling [38]
  - ♦ Spill value once per block, if possible
  - ♦ Avoids redundant loads & stores
- Best of three spilling [38]
  - ♦ Simplify/Select is cheap relative to Build/Coalesce
  - ♦ Try it with several different heuristics
- Rematerialization [55]
  - ♦ Recognize values that are cheaper to recreate
  - ♦ Rather than spill them, rematerialize them
- Spill partial live ranges

Each of these helps

Better Spill Choice Heuristics

- Clean spilling
  - ♦ Minor computations during spill insertion
  - ♦ Mostly a matter of paying attention to details

Every one should do it

- Best of three spilling
  - ♦ Just repeat Simplify/Select with different heuristics
  - ♦ Gets at random parts of the algorithm (***NP**-noise*)
  - ♦ Might get some of it by renumbering – min of seven

20% idea

- Rematerialization
  - ♦ Tag each value with c_i , **BOT**, or **TOP**
  - ♦ Propagate, performing meet at Ø-functions
  - ♦ Modify spill cost computation & spill insertion

20% idea

Rematerialization

Never-killed **values can be rematerialized** (*rather than spilled*)

- Operands are always available
- Computed in a single operation

} Definition of "never-killed" *i.e.,* loadI, offset + FP

Cheaper to recompute than to store & reload (*the classic spill*)

Allocator must

- Discover & mark never-killed **LR**s
- Reflect rematerialization in spill costs
- Use all this knowledge to generate right spills

Chaitin rematerialized LRs that were entirely never-killed

- ♦ We can do partial **LR**s

Rematerialization

Big Picture

- Use SSA to break **LR** into component values
- Tag each component with a value
- Use Wegman & Zadeck **SCCP** to propagate tags
- Split off never-killed parts from rest of **LR**
  - ♦ Use a "special" copy operation
  - ♦ Special copies get coalesced with conservative coalescing
- Use tags to compute spill costs & to insert spill code
- Rely on conservative coalescing and biased coloring to remove unproductive splits (as before)

TOP	defined by **COPY** or Ø
inst	never-killed op (ptr)
BOT	defined by other op

Spilling Partial Live Ranges

- Bottom-up splitting [81,82]
  - ♦ Break uncolored live range into basic blocks
  - ♦ Recombine them when it does not increase degree

No data on how this does with Chaitin-Briggs

- Aggressive splitting [49]
  - ♦ Split aggressively based on the CFG
  - ♦ Undo non-productive splits

Improvements ran from + 4x to - 4x spill ops

- Interference region spilling [37]
  - ♦ Spill just region that conflicts with colored nodes
  - ♦ Run in competition with default spilling

Improvements of ~36% in spill ops vs. Briggs

- Passive splitting [106, 98]
  - ♦ Use directed interference graph to identify splits
  - ♦ Run in competition with default spilling

Sometimes wins big vs. Bergner, sometimes loses

Interference Region Spilling

Simple idea:

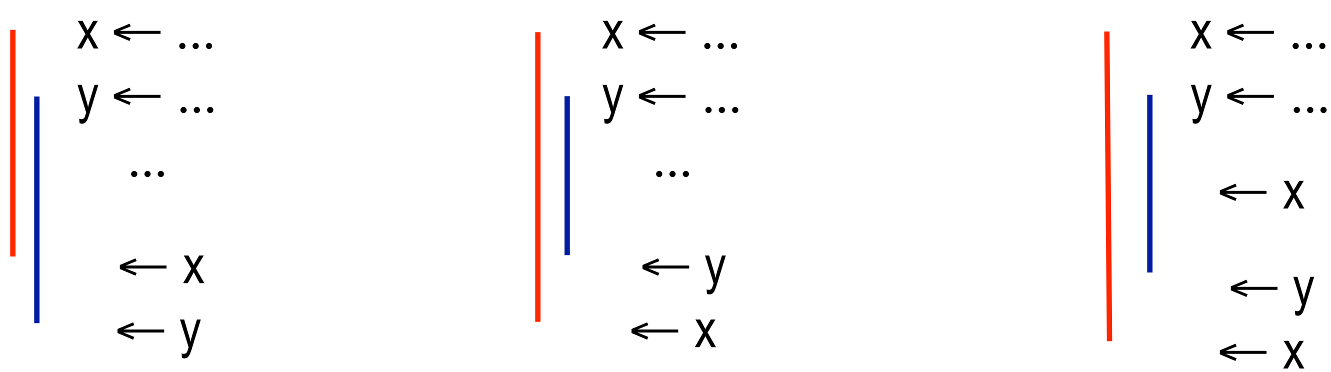
- Find region where *i* & *j* are both live
- Spill *i* around this interference region (IR)
- Can reduce total cost of spilling *i*
- Fits entirely in "Insert Spills" phase of a Briggs allocator

The implementation

- Take colored subgraph and list of uncolored nodes
- For each uncolored LR, find subranges that can be colored
  - ♦ Rest of LR is its IR
- Compare cost of spilling IR versus cost of spilling entire LR
  - ♦ Take cheaper alternative

Passive Splitting

Key observation

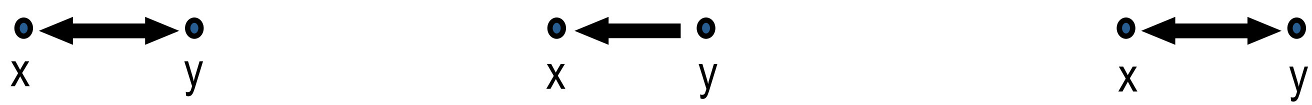


spilling x does not help with y

spilling x helps with y

spilling x does not help with y

The <u>containment</u> graph captures this effect
It is just a directed analog of the interference graph



Passive Splitting

x ← y and not y ← x suggests splitting x around y

To split x around y

- *store x before each definition of y*
- *load x after each death of y*

What does it cost?

- *one memory op at each border of the overlap region*
- *may (or may not) be cheaper than spilling x everywhere*

This is the base case

In practice, we may need to split around several live ranges

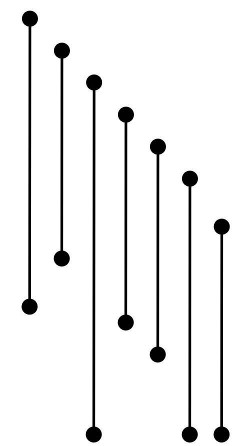
Linear Scan Allocation

Coloring allocators are often viewed as too expensive for use in JIT environments, where compile time occurs at runtime

Linear scan allocators use an approximate interference graph and a version of the bottom-up local algorithm [Poletto & Sarkar]

- Interference graph is an interval graph
  - ♦ *Optimal coloring (without spilling) in linear time*
  - ♦ *Spilling handled well by bottom-up local allocator*
- Algorithm does allocation in a "linear" scan of the graph
- Linear scan produces faster, albeit less precise, allocations

Linear scan allocators hit a different point on the curve of cost versus performance



Live Ranges **in LS**

Interference graph of a set of intervals is an interval graph.

Sun's HotSpot server compiler uses a complete Chaitin-Briggs allocator [279].

Linear Scan Allocation

Building the Interval Graph

- Consider the procedure as a linear list of operations
- A live range for some *name* is an interval (x,y)
  - ♦ x and y are the indices of two operations in the list, with x < y
  - ♦ Every operation where *name* is live falls between x & y, inclusive
    - → Precision of live computation can vary with cost
  - ♦ Interval graph overestimates interference

The Algorithm

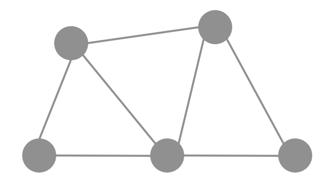
- Use Best's algorithm — bottom-up local
- Distance to next use is well defined
- Algorithm is fast & produces reasonable allocations

Variations have been proposed that build on this scheme

Global Coloring from SSA Form

Observation: The interference graph of a program in SSA form is a chordal graph.

Observation: Chordal graphs can be colored in O(*N*) time.



Chordal Graph

Every cycle of length > 3 has a chord

These two facts suggest allocation using an interference graph built from SSA Form

- Chaitin-Briggs works from live ranges that qre a coalesced version of SSA names
- **SSA** allocators use raw **SSA** names as live ranges
- Allocate live ranges, then insert copies for ϕ-functions

SSA-based allocation has created a lot of excitement in the last couple of years.

See Hack, Grund, and Goos, “Register allocation for programs in **SSA**-form,’ 15th International Conference on Compiler Construction (CC ‘06}, 2006, pages 247-262.

Global Coloring from SSA Form

Coloring from SSA Names has its advantages

- If graph is *k*-colorable, it finds the coloring
  - (*Opinion*) An **SSA**-based allocator will find more *k*-colorable graphs than a live-range based allocator because **SSA** names are shorter and, thus, have fewer interferences.
- Allocator should be faster than a live-range allocator
  - Cost of live analysis folded into **SSA** construction, where it is amortized over other passes
  - Biggest expense in Chaitin-Briggs is the Build-Coalesce phase, which SSA allocator avoids, as it destroys the chordal graph

Global Coloring from SSA Form

Coloring from SSA Names has its disadvantages

- Coloring is rarely the problem
  - Most non-trivial codes spill; on trivial codes, both SSA allocator and classic Chaitin-Briggs are overkill. (Try linear scan?)
- SSA form provides no obvious help on spilling
  - Shorter live ranges will produce local spilling (good & bad)
  - May increase spills inside loops
- After allocation, code is still in SSA form
  - Need out-of-SSA translation
  - Introduce copies after allocation, which may create need to spill
- Need a post-allocation coalescing phase
  - Algorithms exist that do not use an interference graph
  - They are not as powerful as the Chaitin-Briggs coalescing phase

Loop-carried value cannot spill before the loop, since its name is only live inside the loop and after the loop.

TAANSTAAFL: The problem is still **NP**-Complete. Changing the definition of live range does not make it solvable to optimality in polynomial time.

What About A Hybrid Approach ?

How can the compiler attain both speed and precision?

Observation: lots of procedures are small & do not spill

Observation: some procedures are hard to allocate

Possible solution:

- Try different algorithms
- First, try linear scan
  - It is cheap and it may work
- If linear scan fails, try heavyweight allocator of choice
  - Might be Chaitin-Briggs, SSA, or some other algorithm
  - Use expensive allocator only when cheap one spills

This approach would not help with the speed of a complex compilation, but it might compensate on simple compilations

An Even Stronger Global Allocator

Hierarchical Register Allocation (Koblenz & Callahan)

- Analyze control-flow graph to find hierarchy of tiles
- Perform allocation on individual tiles, innermost to outermost
- Use summary of tile to allocate surrounding tile
- Insert compensation code at tile boundaries ($LR_x \rightarrow LR_y$)

Strengths

→ Decisions are largely local

→ Use specialized methods on individual tiles

→ Allocator runs in parallel

Weaknesses

→ Decisions are made on local information

→ May insert too many copies

Still, a promising idea

- Anecdotes suggest it is fairly effective
- Target machine is multi-threaded multiprocessor (Tera MTA)

Eckhardt's MS (Rice, 2005) shows that K&C produces better allocations than C&B, but is much slower

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