CSCI 742 - Compiler Construction

Lecture 40

Register Allocation

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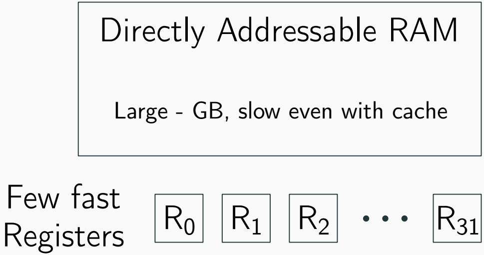
Register Machines

Better for most purposes than stack machines

- Closer to modern CPUs (RISC architecture)
- Closer to control-flow graphs
- Simpler than stack machine (but register set is finite)

Examples:

- RISC: ARM architecture, RISC-V
- CISC: x86 architecture



Basic Instructions of Register Machines

- $R_i \leftarrow Mem[R_j]$ load
- $Mem[R_j] \leftarrow R_i$ store
- $R_i \leftarrow R_j \oplus R_k$ compute: for an operation $\oplus$

Efficient register machine code uses as few loads and stores as possible

State Mapped to Register Machine

Both dynamically allocated heap and stack expand

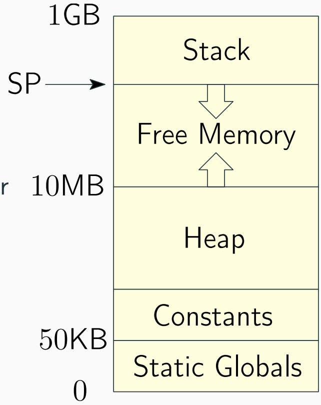
- Heap need not be contiguous; can request more memory from the OS if needed
- Stack grows downwards

Heap is more general:

- Can allocate, read/write, and deallocate, in any order
- Garbage Collector does deallocation automatically
  - Must be able to find free space among used one, group free blocks into larger ones (compaction),...

Stack is more efficient:

- Allocation is simple: increment, decrement
- Top of stack pointer (SP) is often a register
- If stack grows towards smaller addresses:
  - to allocate N bytes on stack (push): $SP := SP - N$
  - to deallocate N bytes on stack (pop): $SP := SP + N$



(Exact picture may depend on hardware and operating system)

JVM vs. General Register Machine Code

- Naïve Correct Translation

JVM:	Register Machine:
`imul`	$R_1 \leftarrow$ Mem[SP]
	SP = SP + 4
	$R_2 \leftarrow$ Mem[SP]
	$R_2 \leftarrow R_1 * R_2$
	Mem[SP] $\leftarrow R_2$

Example: How many variables?

- Do we need 7 distinct registers if we wish to avoid load and stores?
- Variables: `x` , `y` , `z` , `xy` , `yz` , `xz` , `r`

```
x = m[0];
y = m[1];
xy = x * y;
z = m[2];
yz = y*z;
xz = x*z;
r = xy + yz;
m[3] = r + xz;
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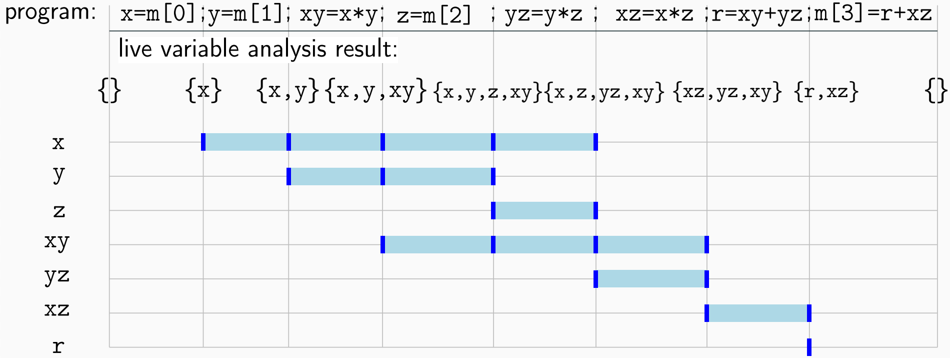
```
x = m[0];
y = m[1];
xy = x * y;
z = m[2];
yz = y*z;
y = x*z;      // reuse y
x = xy + yz; // reuse x
m[3] = x + y;
```

- Can do it with 5 only!

Idea of Register Allocation



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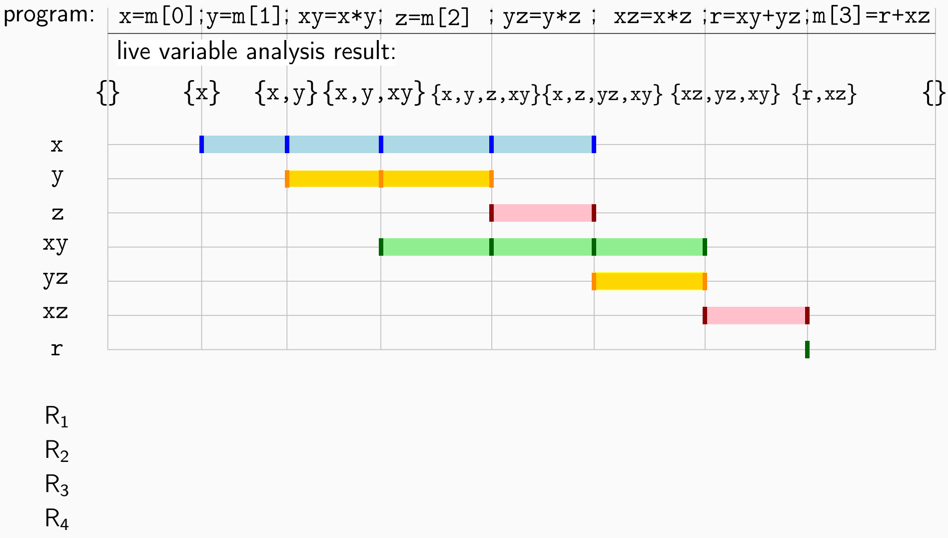

- Each color denotes a register
- Avoid overlap of same colors
- 4 registers are enough for this 7-variable program

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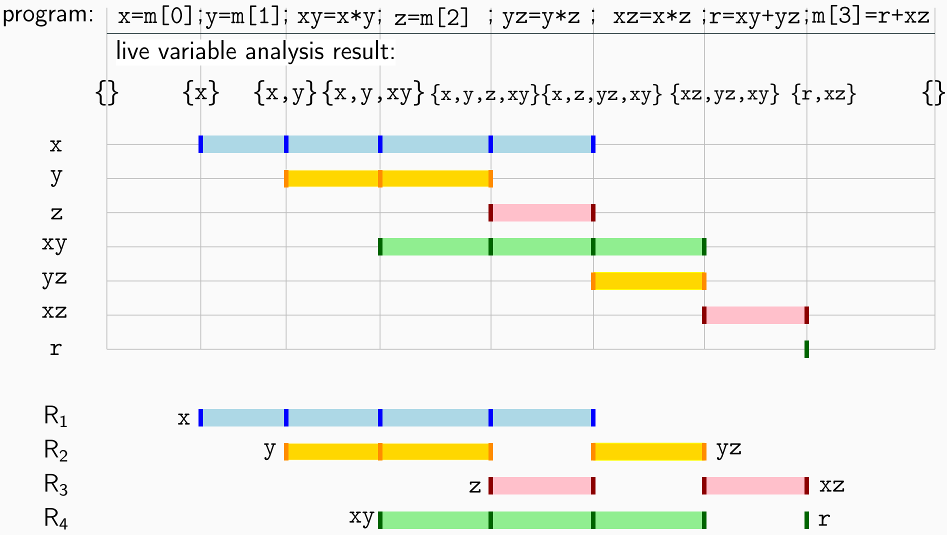

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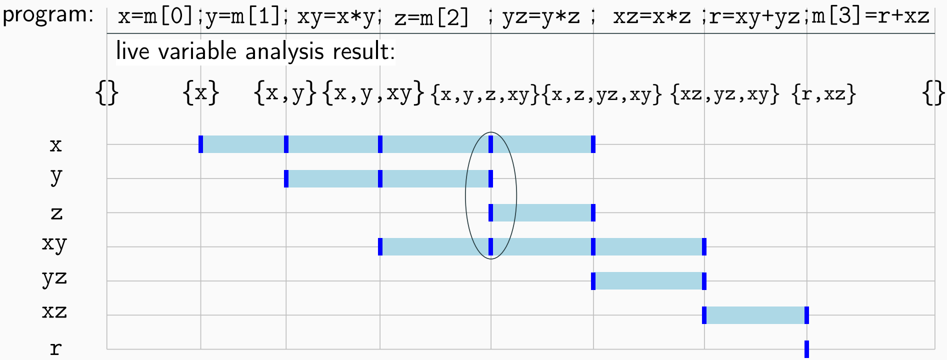
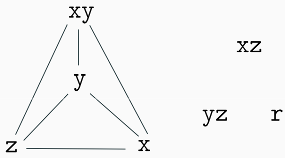


- For each pair of variables determine if there is a point at which they are both alive
- Construct interference graph



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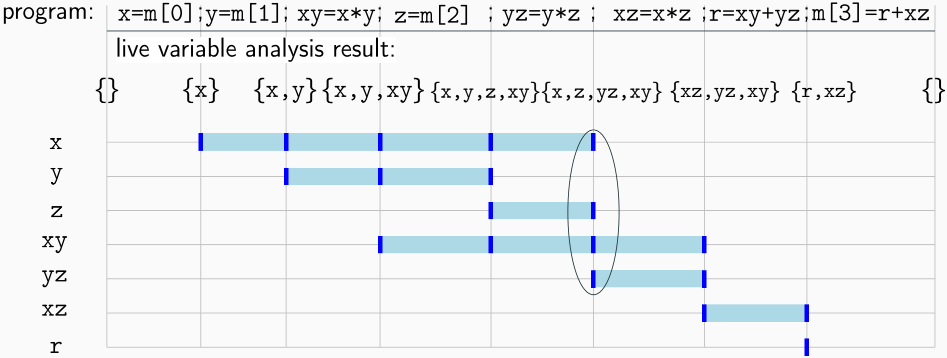

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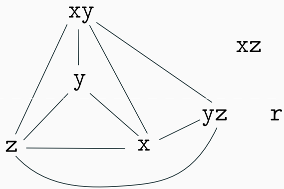

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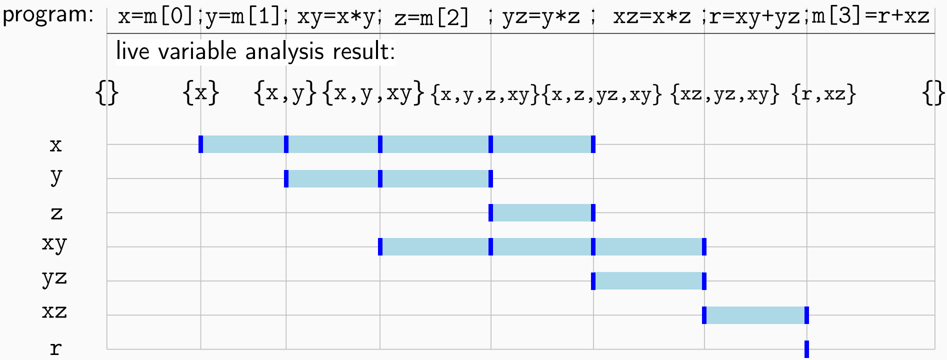

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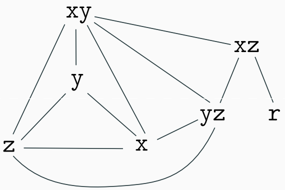

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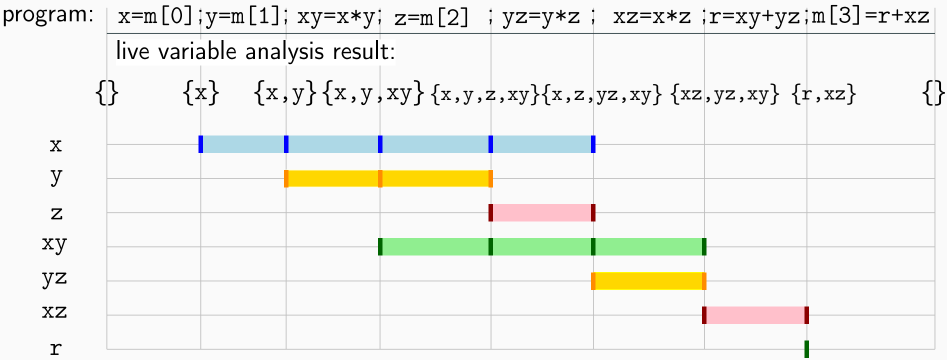
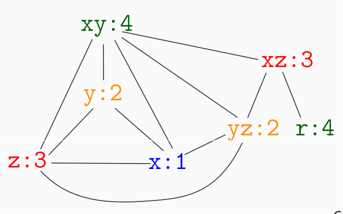


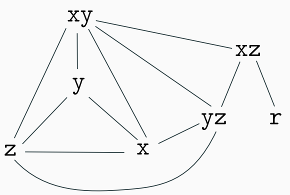
- Need to assign colors (register numbers) to nodes such that:
- If there is an edge between nodes, then those nodes have different colors
- Standard graph vertex coloring problem



Register Interference Graph (RIG)

- Indicate whether there exists a point of time where both variables are live
- Look at the sets of live variables at all program points after running live-variable analysis
- If two variables occur together, draw an edge
- We aim to assign different registers to such these variables
- Finding assignment of variables to K registers:
  corresponds to coloring graph using K colors

Graph Coloring Problem



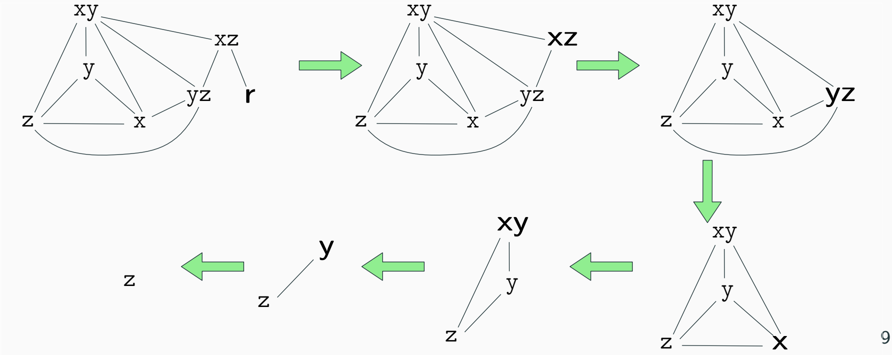
- NP hard
- In practice, we have heuristics that work for typical graphs
- If we cannot fit it all variables into registers, perform a **spill**: Store variable into memory and load later when needed

Heuristic for Coloring with K Colors

Simplify:

- If there is a node with less than K neighbors, we will always be able to color it!
- So we can remove such node from the graph
  - (if it exists, otherwise remove other node)
- This reduces graph size. It is useful, even though incomplete

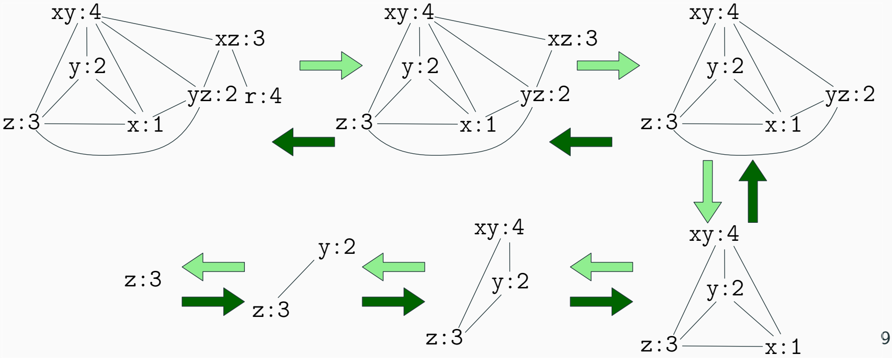
(e.g. can color planar by at most 4 colors, yet can have nodes with many neighbors)



Heuristic for Coloring with K Colors

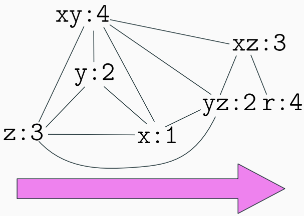
Select:

- Assign colors backwards, adding nodes that were removed
- If the node was removed because it had $< K$ neighbors, we will always find a color
- If there are multiple possibilities, we can choose any color



Use Computed Registers

```
x = m[0];
y = m[1];
xy = x * y;
z = m[2];
yz = y*z;
xz = x*z;
r = xy + yz;
m[3] = res1 + xz;
```




```
R1 = m[0]
R2 = m[1]
R4 = R1*R2
R3 = m[2]
R2 = R2*R3
R3 = R1*R3
R4 = R4 + R2
m[3] = R4 + R3
```

Summary of Heuristic for Coloring

Simplify (forward, safe):

If there is a node with less than K neighbors, we will always be able to color it, so we can remove it from the graph

Potential Spill (forward, speculative):

If every node has K or more neighbors, we still remove one of them we mark it as node for potential spilling. Then remove it and continue

Select (backward):

Assign colors backwards, adding nodes that were removed

- If we find a node that was spilled, we check if we are lucky, that we can color it. If yes, continue
- If not, insert instructions to save and load values from memory (**actual spill**)
  Restart with new graph
  (graph is now easier to color as we killed a variable)