

# CMPT 379

## Compilers

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# Code Generation

- Instruction selection
- Register allocation
- Stack frame allocation ✓
- Static or global allocation ✓
- Basic blocks and Flow graphs
- Transformations on Basic blocks

# Code Generation

- Produce code that is correct
- Produce code that is of high quality (size and speed)
- The problem of generating optimal code is *undecidable*
- In practice, we need heuristics that generate good, but perhaps not optimal, code

# Instruction Costs

- Since optimal code generation is not possible a useful way to think about the problem is as an *optimization* problem
- Each instruction can be assigned a cost
  - For complex instruction sets some instructions can be more preferable than others
- Using registers have zero cost, while using memory locations is costlier
- If each instruction is equally expensive, this will minimize the number of instructions as well

# Register Allocation

- Code generation either directly to assembly or from 3-address code (TAC)
- For each location, we have to find a register to store values or temporary values
  - Problem: limited number of registers
- Compiler has to find optimal assignment of locations to registers
  - Register use can involve stacked temporaries or other ways to reuse registers
- If no more registers available, we *spill* a location into memory

# Register Allocation

- Bind locations to registers for all or part of a function
- Dynamic Optimization Problem
  - Not compile-time, but run-time frequency is what counts
- Heuristics
  - Allocate registers for variables likely to be used frequently
  - Keep temporaries in registers → minimize their number
- Register Allocation using **Liveness Analysis**

# Basic Blocks

- Functions transfer control from one place (the caller) to another (the called function)
- Other examples include any place where there are branch instructions
- A *basic block* is a sequence of statements that enters at the start and ends with a branch at the end
- Remaining task of code generation is to create code for basic blocks and branch them together

# Blocks

```
main()
{
    int a = 0; int b = 0;
    {
        int b = 1;
        {
            int a = 2; printf(“%d %d\n”, a, b);
        }
        {
            int b = 3; printf(“%d %d\n”, a, b);
        }
        printf(“%d %d\n”, a, b);
    }
    printf(“%d %d\n”, a, b);
}
```

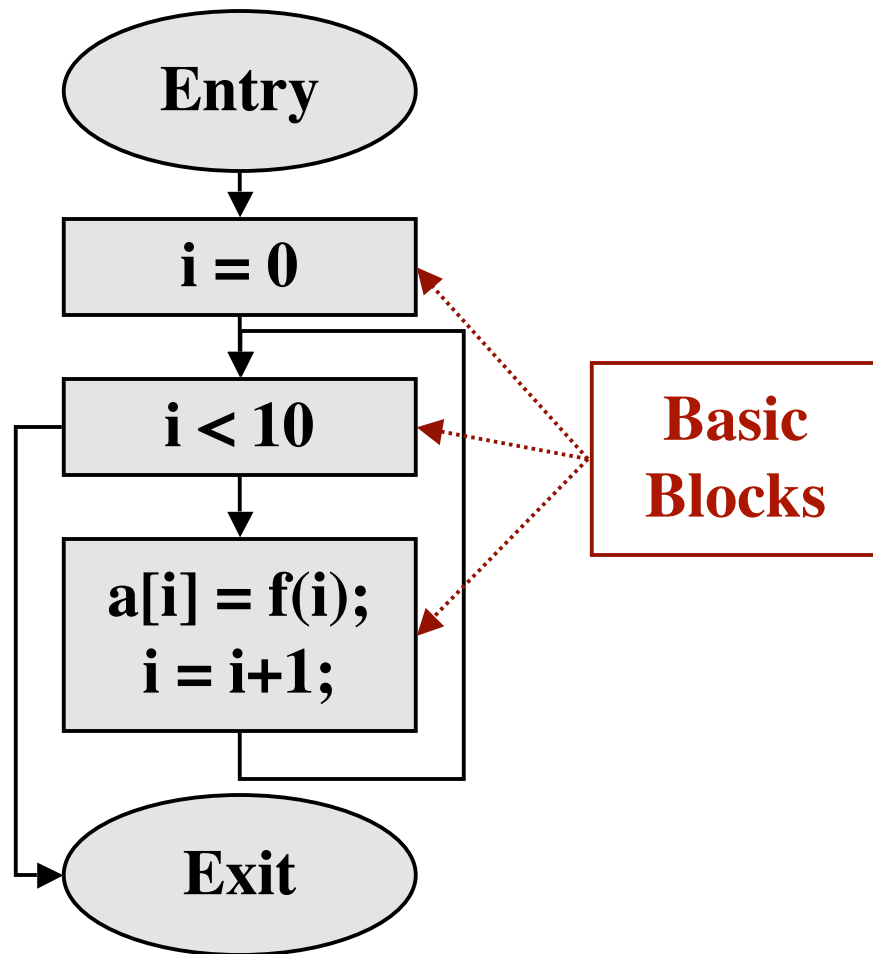


# Partition into Basic Blocks

- Input: sequence of TAC instructions
  1. Determine set of leaders, the 1st statement of each basic block
    - a) The 1st statement is a leader
    - b) Any statement that is the target of a conditional jump or goto is a leader
    - c) Any statement immediately following a conditional jump or goto is a leader
  2. For each leader, the basic block contains all statements upto the next leader

# Control Flow Graph (CFG)

```
int main() {  
    extern int f(int);  
    int i;  
    int *a;  
    for (i = 0;  
        i < 10;  
        i = i + 1)  
        { a[i] = f(i); }  
}
```



# Control Flow Graph in TAC

**main:**

**BeginFunc 72 ;**

**i = 0 ;**

**L0:**

**tmp1 = 10 ;**

**tmp2 = i < tmp1 ;**

**IfZ tmp2 Goto L1 ;**

**tmp3 = 4 ;**

**tmp4 = tmp3 \* i ;**

**tmp5 = a + tmp4 ;**

**param i #0 ;**

**tmp6 = call f ;**

**pop 4 ;**

**\*(tmp5) = tmp6 ;**

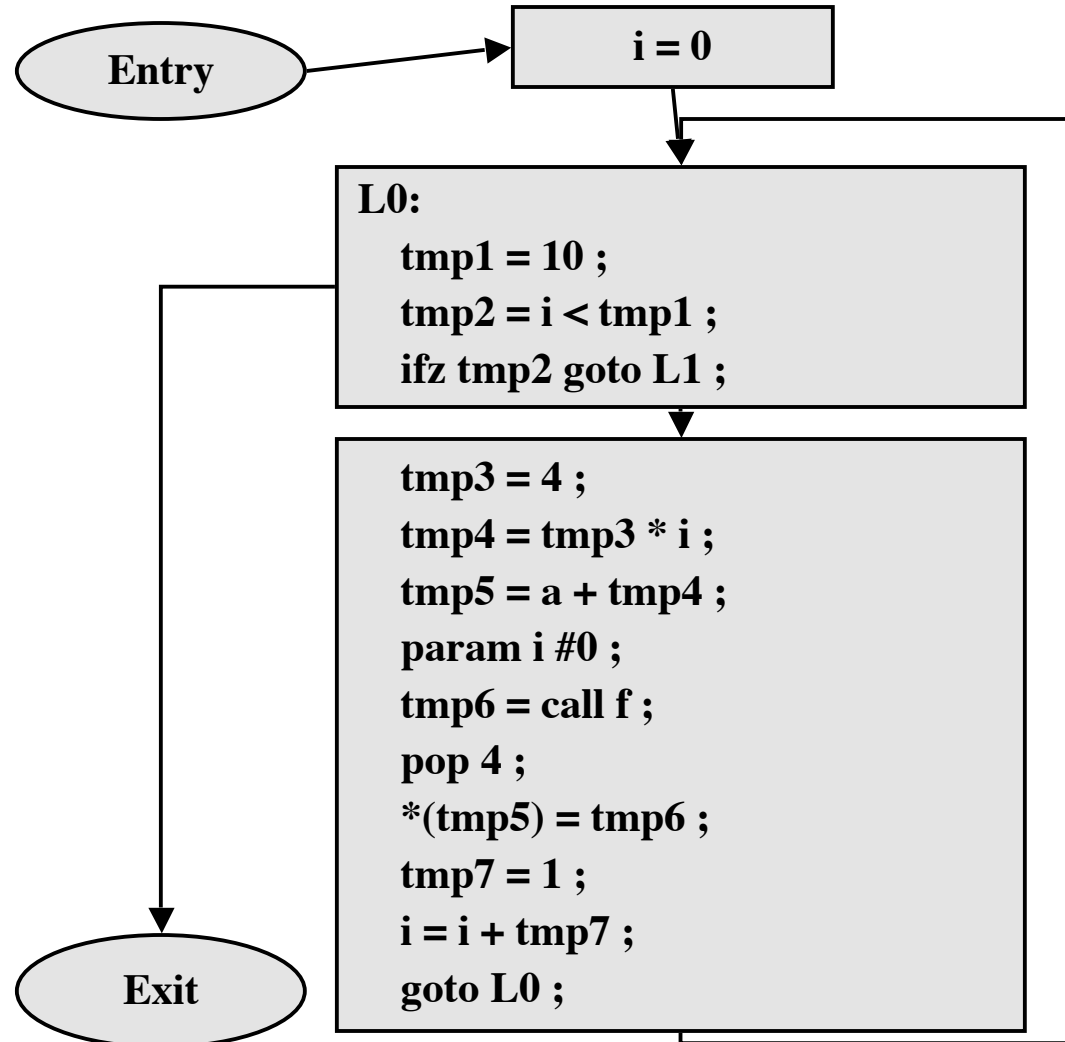
**tmp7 = 1 ;**

**i = i + tmp7 ;**

**goto L0 ;**

**L1:**

**EndFunc ;**



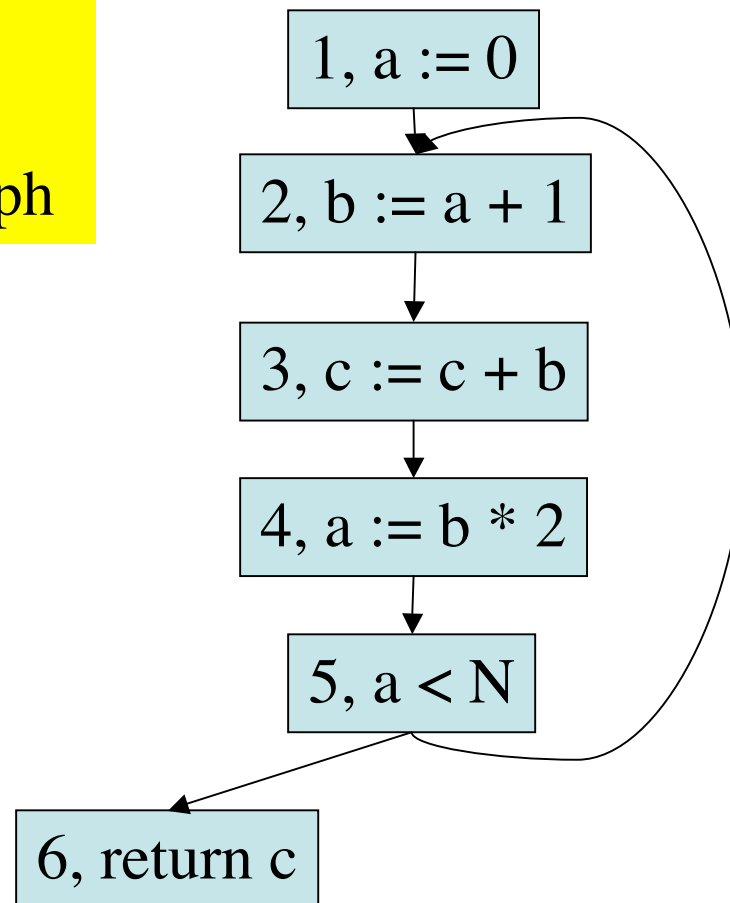
# Dataflow Analysis

- Compute Dataflow Equations over Control Flow Graph
- Liveness Analysis:  
$$\text{in}[\text{BB}] := \text{use}[\text{BB}] \cup (\text{out}[\text{BB}] - \text{def}[\text{BB}])$$
$$\text{out}[\text{BB}] := \bigcup \text{in}[s] : \text{forall } s \in \text{succ}[\text{BB}]$$
- Computation by fixed-point analysis

# Liveness Analysis

```
a := 0
L1: b := a + 1
    c := c + b
    a := b * 2
    if a < N goto L1
    return c
```

build a  
control  
flow graph



# Liveness Analysis

- Liveness Analysis:

$\text{in}[\text{BB}] := \text{use}[\text{BB}] \cup (\text{out}[\text{BB}] - \text{def}[\text{BB}])$

$\text{out}[\text{BB}] := \bigcup \text{in}[s] : \text{forall } s \in \text{succ}[\text{BB}]$

- Fixed point computation:

for each  $n$ : **in** $[n] := \{\}$ ; **out** $[n] := \{\}$

repeat

for each  $n$ :

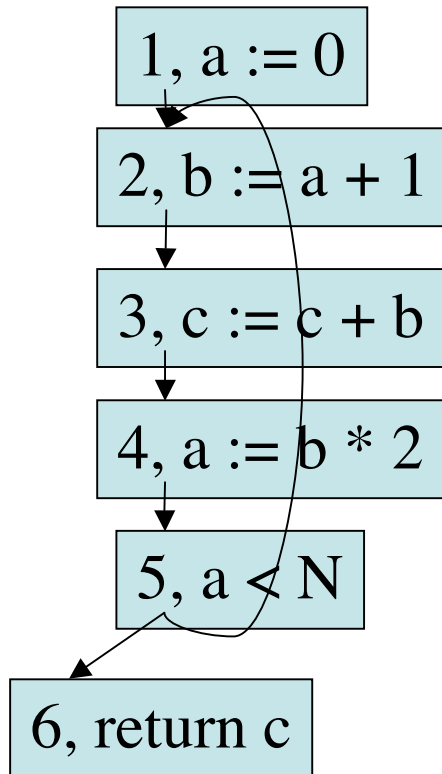
**in'** $[n] := \text{in}[n]$ ; **out'** $[n] := \text{out}[n]$

**in** $[n] := \text{use}[n] \cup (\text{out}[n] - \text{def}[n])$

**out** $[n] := \bigcup \text{in}[s] : \text{forall } s \in \text{succ}[n]$

until **in'** $[n] == \text{in}[n]$  && **out'** $[n] == \text{out}[n]$  for all  $n$

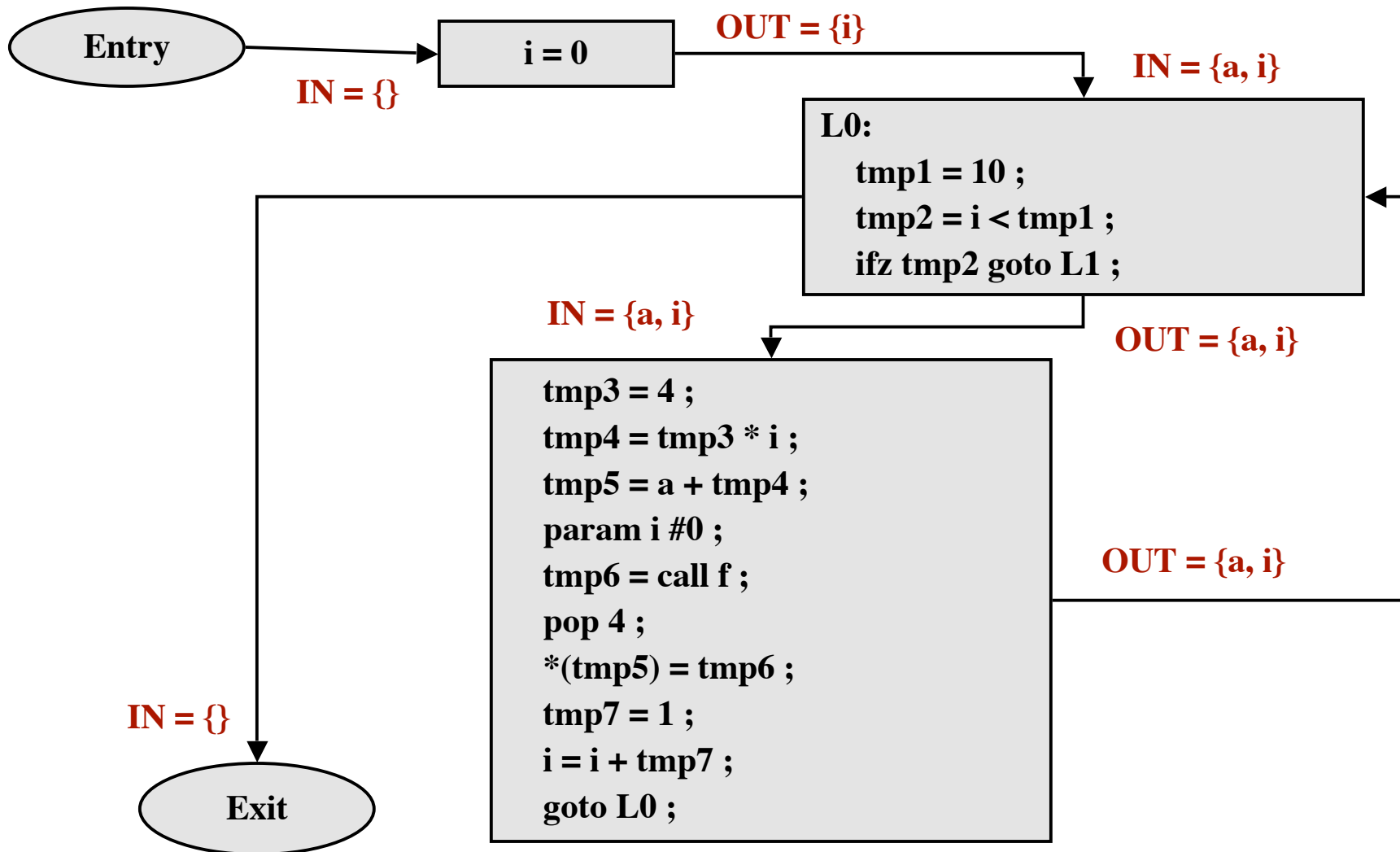
# Liveness Analysis



		1st	2nd	3rd	4th	5th	6th	7th
	use/def	in/out	in/out	in/out	in/out	in/out	in/out	in/out
1	a		a	a	ac	c ac	c ac	c ac
2	a b	a	a bc	ac bc	ac bc	ac bc	ac bc	ac bc
3	bc c	bc	bc b	bc b	bc b	bc b	bc bc	bc bc
4	b a	b	b a	b a	b ac	bc ac	bc ac	bc ac
5	a	a a	a ac	ac ac	ac ac	ac ac	ac ac	ac ac
6	c	c	c	c	c	c	c	c

can we do this faster? try going from 6 down to 1 instead

# Liveness Analysis

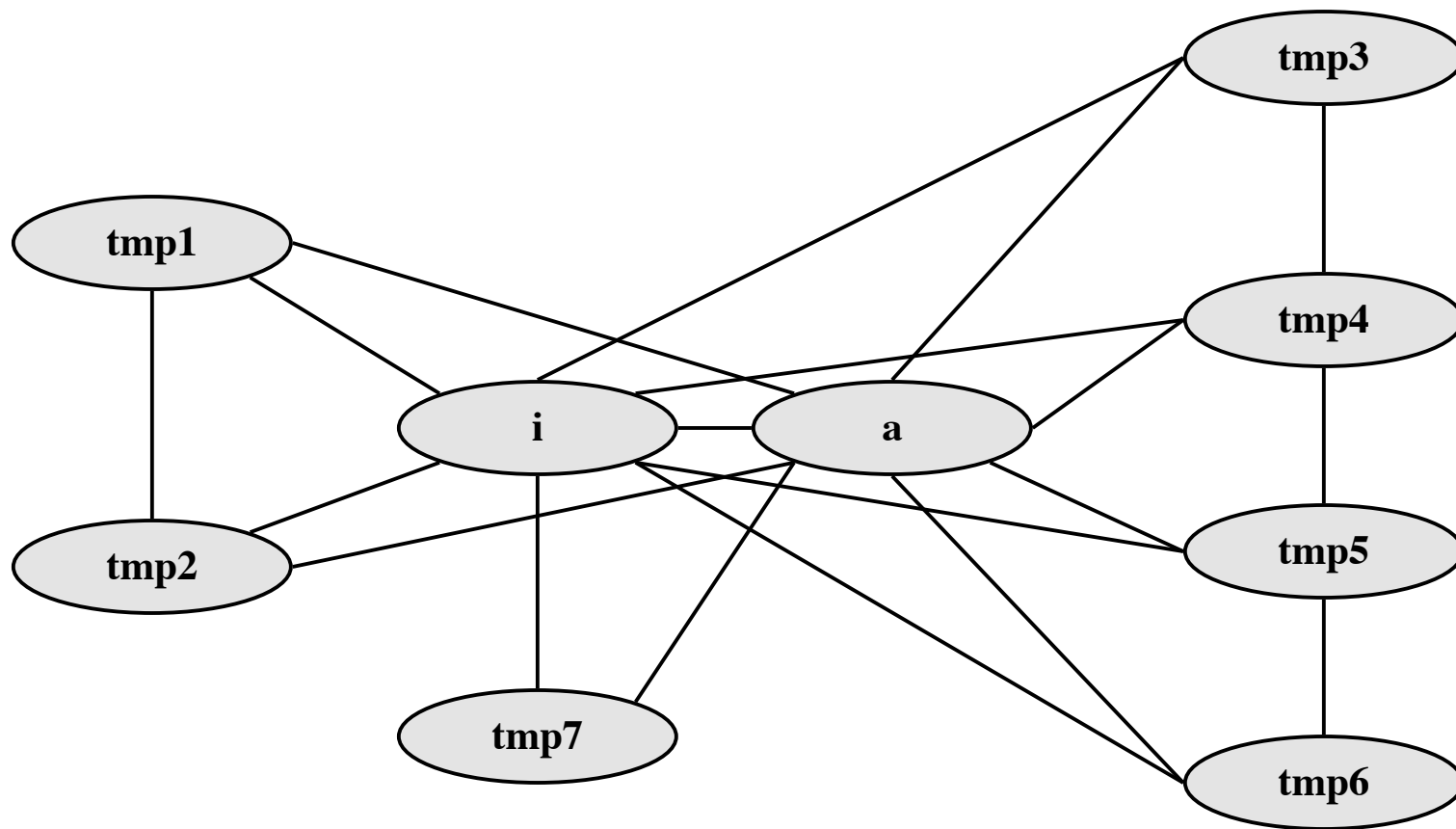




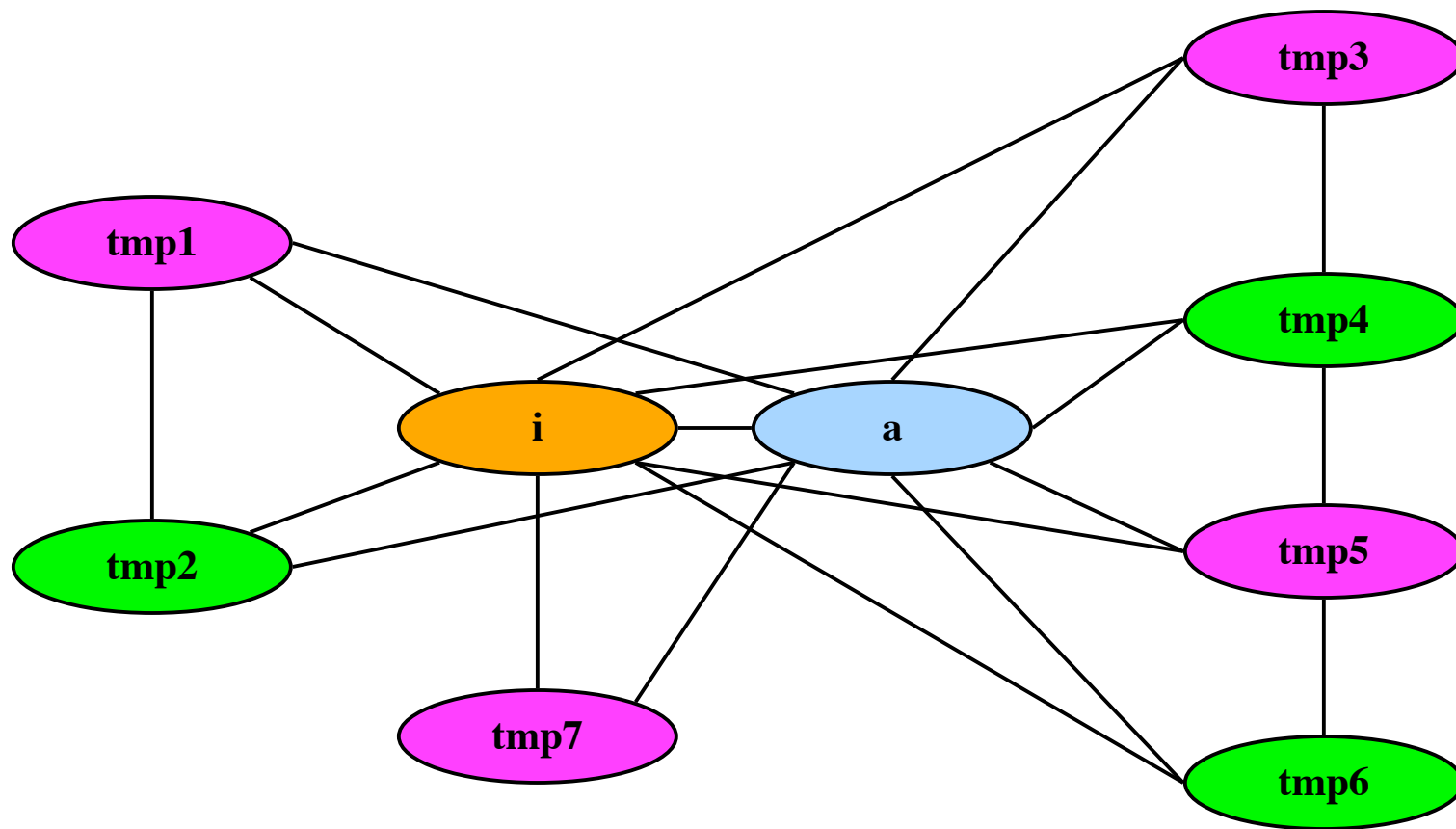
# Register Allocation

- Do liveness analysis on Control Flow Graph
  - Straightforward (iteration-less) computation within basic block
  - Compute live ranges for each location
- Build interference graph
  - Two locations are connected if their live ranges overlap

# Interference Graph



# Colored Interference Graph



# Register Allocation as Graph Coloring

- First pass: use as many symbolic registers as needed including registers for stack pointers, frame pointers, etc.
- Register Interference Graph
  - Two nodes in the graph are connected if their live ranges overlap
- Color interference graph
  - Result is register assignment --  $k$  colors for  $k$  registers

# Register Allocation as Graph Coloring

- Second pass: assign physical registers to symbolic ones
  - Construct a **register interference graph** (nodes are symbolic registers and edge denotes that they cannot be assigned to the same physical register)
  - Attempt to  $k$ -color the interference graph, where  $k$  is the number of available registers
  - $k$ -coloring a graph is NP-complete

# Register Allocation as Graph Coloring

- Algorithm for solving whether a graph  $G$  is  $k$ -colorable:
- Pick any node  $n$  with fewer than  $k$  neighbours
- Remove  $n$  and adjacent edges to create a new graph  $G'$
- $k$ -coloring of  $G'$  can be extended to  $k$ -coloring to  $G$  by assigning to  $n$  a color that is not assigned to any of  $n$ 's neighbours
- If we cannot extend  $G'$  to  $G$ , then  $k$ -coloring of  $G$  is not possible

# Register Allocation as Graph Coloring

- If every node in  $G$  has more than  $k$  neighbours,  $k$ -coloring of  $G$  is not possible
- Take some node  $n$  and spill into memory, remove it from the graph and continue  $k$ -coloring
- Spilling = generating code to store contents of register to memory and when location is used generate code to load from memory into an available register (by spilling another location)

# Register Allocation as Graph Coloring

- Many different heuristics for picking a node  $n$  to spill
- E.g. avoid introducing spilling symbolic registers that are inside loops or heavily visited regions of code
- C allows a *register* and a *volatile* keyword to direct the compiler whether a variable contains a value that is heavily used.
- Special case: Register Allocation for Expression Trees (Maximal Munch suffices for this task)



# Summary

- Code generation: from Intermediate Representation (IR) to Assembly
- Three Address Code (TAC) can be easily converted to a *control flow graph*
- The control flow graph allows sophisticated dataflow analysis
- The liveness of each location can be used for register allocation
- Register Allocation as heuristic graph coloring.