Compiler Technology of Programming Languages

Chapter 14

Compiler Optimizations

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Compiler Optimizations

- to minimize or maximize some attributes of an executable program
  - Execution time
  - Code size (e.g. IoT devices)
  - Power (e.g. embedded sensors)
  - Compile time may also be an optimization target

Why Different Optimizations

Q: *Why small code does not necessary yield better runtime?*

Q: *Why faster execution does not always consume less power?*

Q: Why compile time may be more important than code execution time?

Q: Why not leave performance job to Moore's law?

Q: Why not let AI deep learning take over compiler optimizations?

Compiler Optimizations (cont.)

- Optimization Basics
  - Never compromise original program valid behavior
  - Optimization is a misnomer
    - Optimal runtime solutions are often un-decidable
    - Many optimization problems are NP-hard
  - Compile time and space are limited
    - Especially for Runtime compilation such as JIT
  - Some transformations may impede performance for some other cases

➔ Heuristic methods,

➔ Sub-optimal solutions,

➔ Often rely on compiler options/flags controlled by users

Compiler Optimizations (cont.)

- Optimization Roadblocks
  - Static translation
  - Procedure calls
  - Separate compilation
  - Aliasing
  - Debugging needs
  - Parallel execution requirement

    Volatile memory

Optimizations Related Issues

- Machine independent *vs.* Machine dependent optimizations
- Compile time (Static) *vs.* Runtime (Dynamic) tradeoffs (as in JIT or adaptive optimization systems)
- Domain specific *vs.* General purpose optimizations
- Static *vs.* Profile driven *vs.* Runtime optimizations
- Predictive Heuristics vs. Iterative Optimization
- Locality *vs.* Parallelism

Popular PL and Impact on Opt.

Dec 2017	Dec 2016	Change	Programming Language	Ratings	Change
1	1		Java	13.268%	-4.59%
2	2		C	10.158%	+1.43%
3	3		C++	4.717%	-0.62%
4	4		Python	3.777%	-0.46%
5	6	↑	C#	2.822%	-0.35%
6	8	↑	JavaScript	2.474%	-0.39%
7	5	↓	Visual Basic .NET	2.471%	-0.83%
8	17	⇈	R	1.906%	+0.08%
9	7	↓	PHP	1.590%	-1.33%
10	18	⇈	MATLAB	1.569%	-0.25%
11	13	↑	Swift	1.566%	-0.57%
12	11	↓	Objective-C	1.497%	-0.83%
13	9	⇊	Assembly language	1.471%	-1.07%
14	10	⇊	Perl	1.437%	-0.90%
15	12	↓	Ruby	1.424%	-0.72%

Most Popular PL. (2016-2017)

	Indeed	IEEE Spectrum
1	Java	Java
2	JavaScript	C
3	.NET	Python
4	HTML	C++
5	Python	JavaScript
6	SQL	C#
7	C or C++	PHP
8	Node.js	HTML
9	Ruby	Ruby
10	PHP	Swift

A job search site

Dice and CareerBuilder

PL Trend Impact

- More languages require runtime/adaptive translations:

  Java, C#, PHP, Python, JavaScript, Perl, Ruby, AJAX

- More scripting languages:

  Programmers favor languages with simple syntax and semantics

- Optimizations

  Some traditional: constant folding, loop transformations, pointer analysis, …

  Some new: type inference, function caching,..

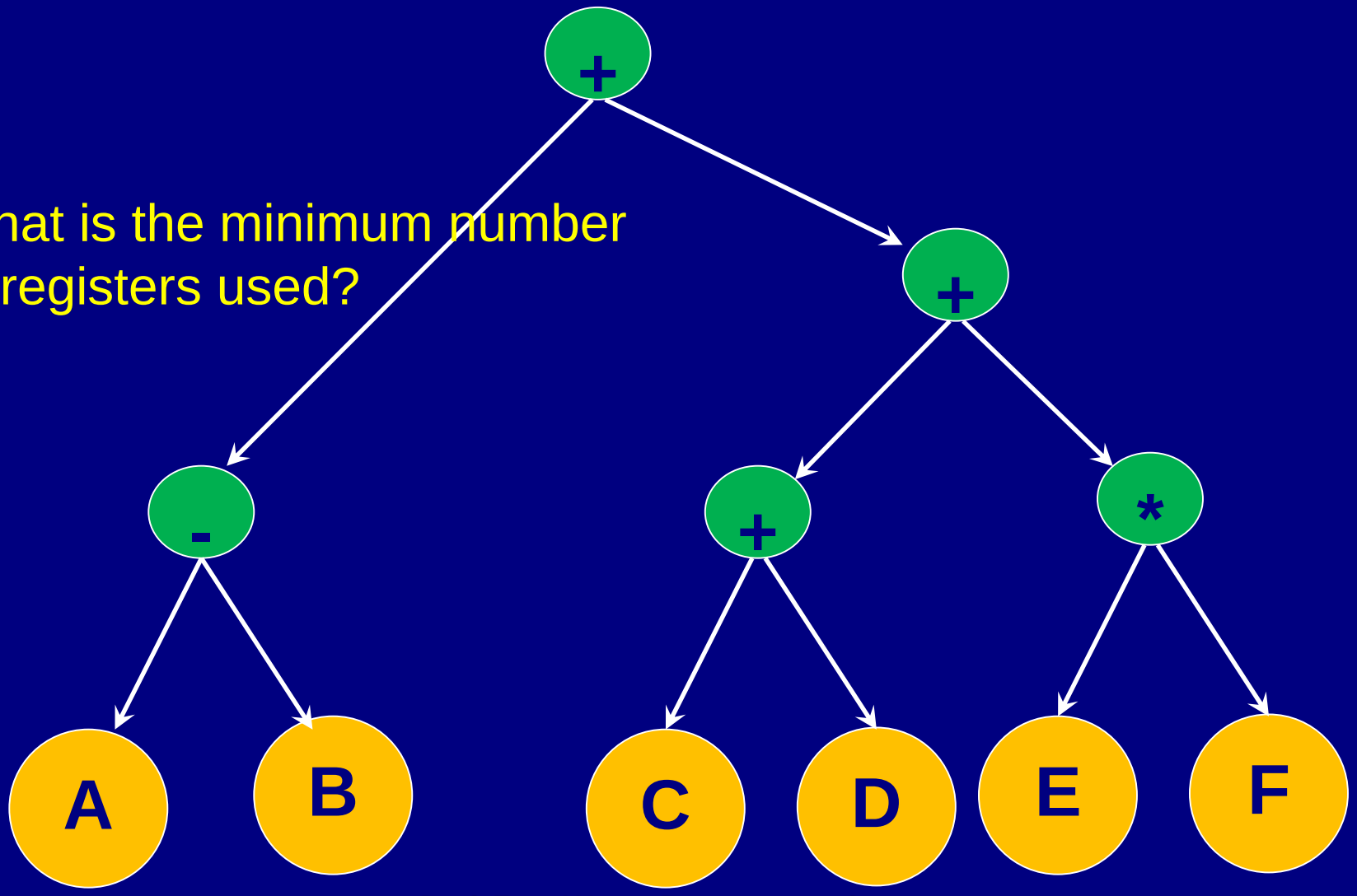
Basic Code Generation Techniques

- Sethi-Ullman (or Ershov) Numbering
- Value Numbering (CSE)
- DAG Building
- Automatic Instruction Selection
- Register Allocation: Graph Coloring
- Local Code Scheduling
- Global Code Scheduling

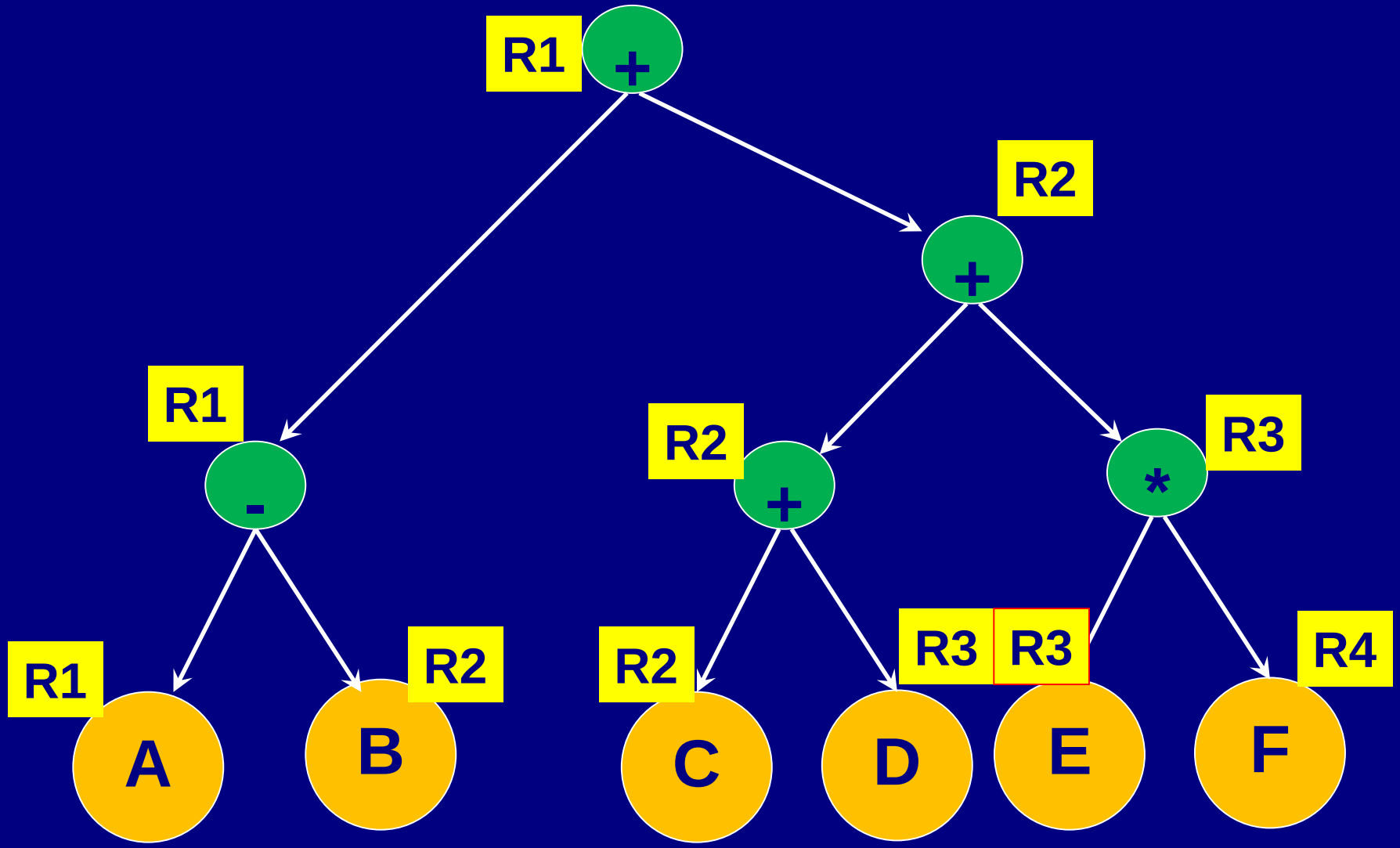
Some Basic Code Generation Techniques

Translating Expression Trees

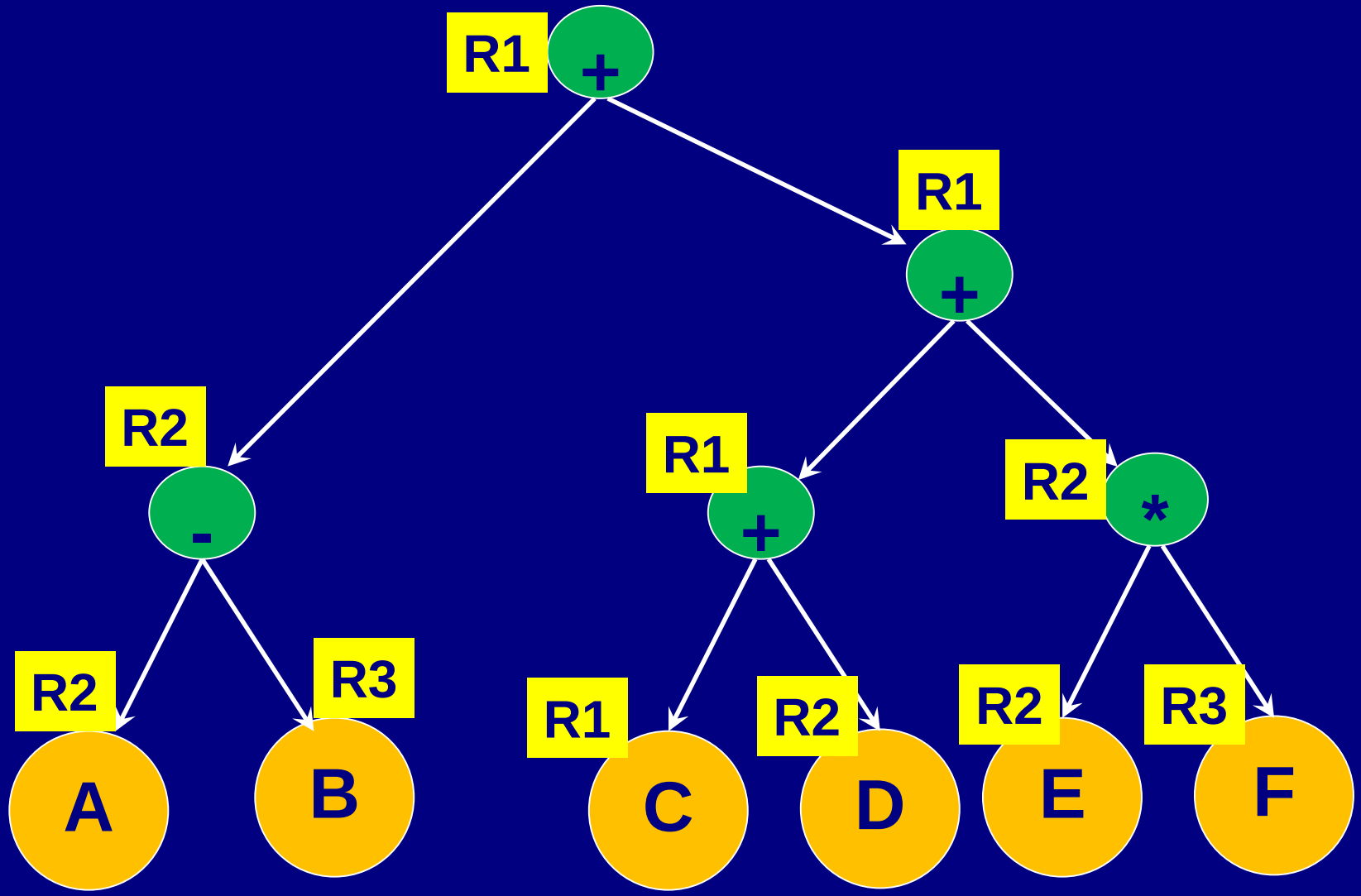
What is the minimum number of registers used?



Translating Expression Trees



Translating Expression Trees

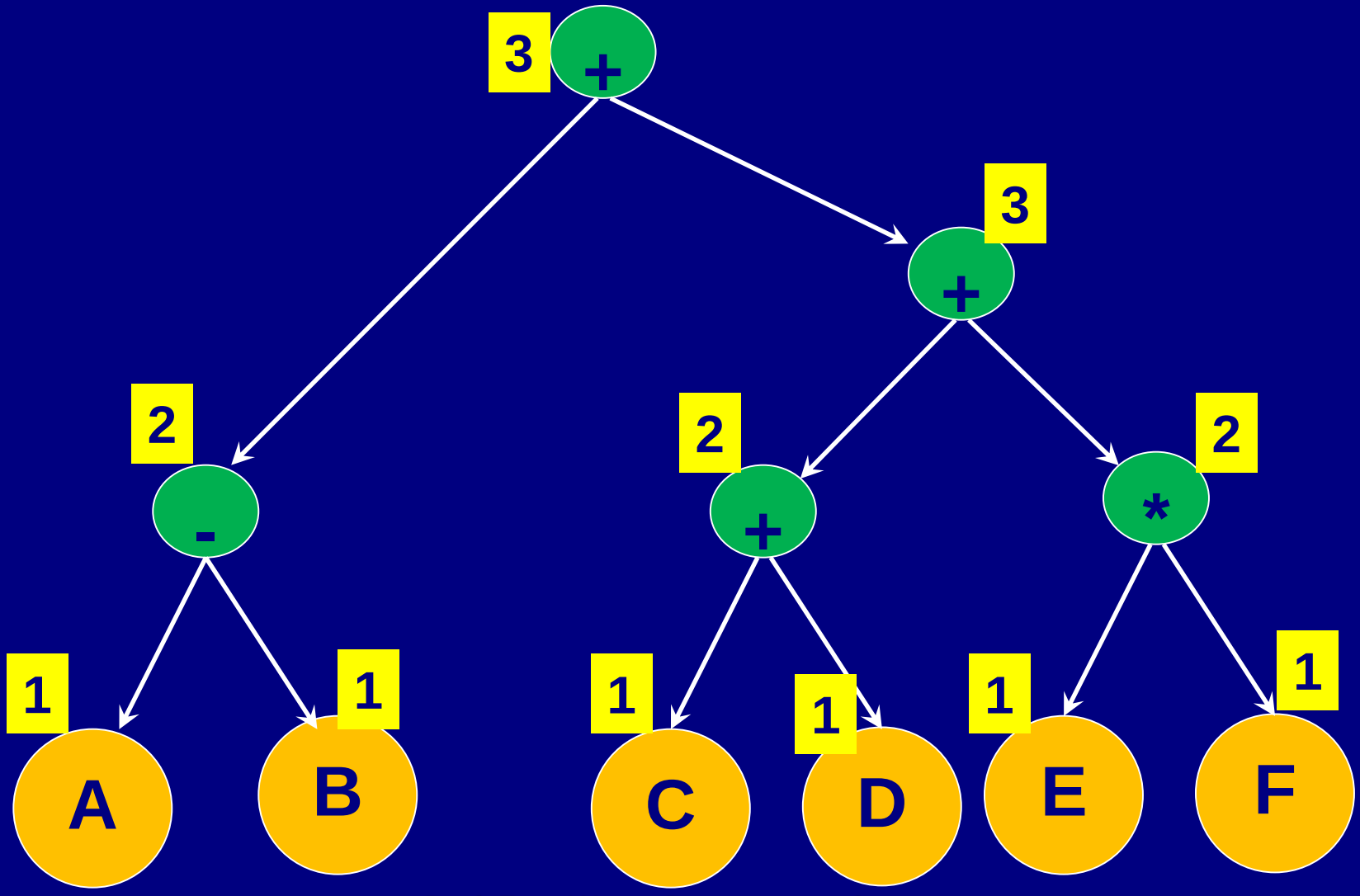


Sethi-Ullman/Ershov Numbering

Determines the minimum number of registers needed to evaluate any expression ***trees***

```
Procedure registerNeeds(T)
If (T.kind == ID or T.kind == const)
    { T.regcount = 1}
else
    {call registerNeeds(T.leftchild);
     call registerNeeds(T.rightchild);
 if (T.leftchild.regcount == T.rightchild.regcount)
     {  T.regcount = T.rightchild.regcount +1; }
 else
     {T.regcount = MAX (T.leftchild.regcount,
      T.rightchild.regcount);}
 end
```

Sethi-Ullman/Ershov Numbering



Sethi-Ullman Numbering Code Gen

TreeCG

- We use regcount labeling to drive code gen
- It generates code to evaluate the tree, leaving the result in the first register on the list.
- If TreeCG is given too few registers, it spills a register to the frame (i.e. activation record)
- If left child has a regcount > right child
  it evaluates left child first, then the right child
  otherwise, it evaluate the right child, then the left child.

Other Considerations

Can the immediate value fit in inst ?

- Some machines allow immediate values to be specified in instructions.
- Some operators are associative, for example, (a+b) + c == a + (b+c)
  Applying associative rule, registers could be reduced, for example:
  (a+b)+(c+d) requires 3 registers
  but a+b+c+d requires only 2 registers

  However, this is not true for FP arithmetic due to rounding issues

Insufficiently Supply of Registers

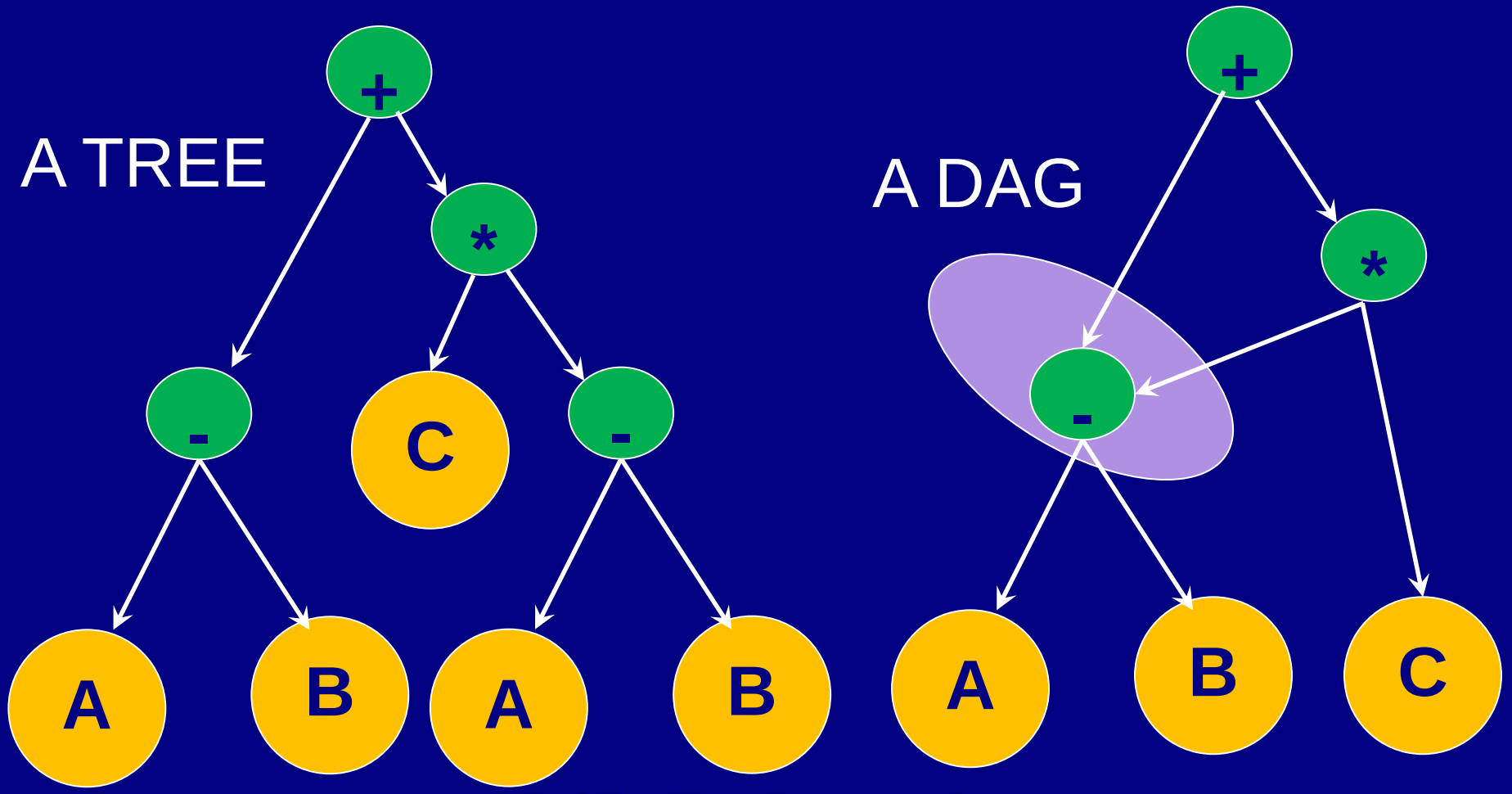
- Assume we have **r** registers available
- If a node N with a label k, k>**r,** we handle each side of the tree separately, and store the result of *larger subtree* (i.e. spill) to AR, and load back the result from AR before node N is evaluated.

CSE (Common Sub-Expressions)

- (A+B) + (A+B)*C
  (A+B) here is called a common sub-expression
- A CSE can be allocated to a register to avoid redundant computations.
- An expression tree captures no CSEs, each operand has only one consumer. A CSE has more than one consumers.
- A DAG (Directed Acyclic Graph) supports CSEs
- Value numbering is an efficient algorithm to identify CSEs in building a DAG

CSE (Common Sub-Expressions)

- (A-B) + (A-B)*C



Local Value Numbering

- Each variable and expression is assigned a unique number
- When the compiler sees a variable or expression, check if it is already assigned a number.
  - If so, use the number for that value
  - If not, assign a new number
- Same number means same value (i.e. an index of an array).

Local Value Numbering

- Example:

A = B + C

D = B + C

E = B

F = E + C

Numbers assigned

B → #1

C → #2

B+C → #1+#2 → #3

A → #3

D → #3

E → #1

E+C → #1+#2 → #3

F → #3

Value Numbering Implementation

- Example:

i=i+j;

k=(i+j)*k;

…

x=(i+j)*k+2

index	type	left	right
1	ID	i	
2	ID	j	
3	+	1	2
4	=	1	3
5	ID	k	
6	*	3	5

Value number means the *index* of the array

Value Numbering Implementation

- Example:

i=i+j;

k=(i+j)*k;

…

x=(i+j)*k+2

index	type	left	right
1	ID	i	
2	ID	j	
3	+	1	2
4	=	1	3
5	ID	k	
6	*	3	5

How to locate the expression (i+j) quickly in the table? Hint: this is a sequential table

Hash – take (+, I, j) and generate a hash value

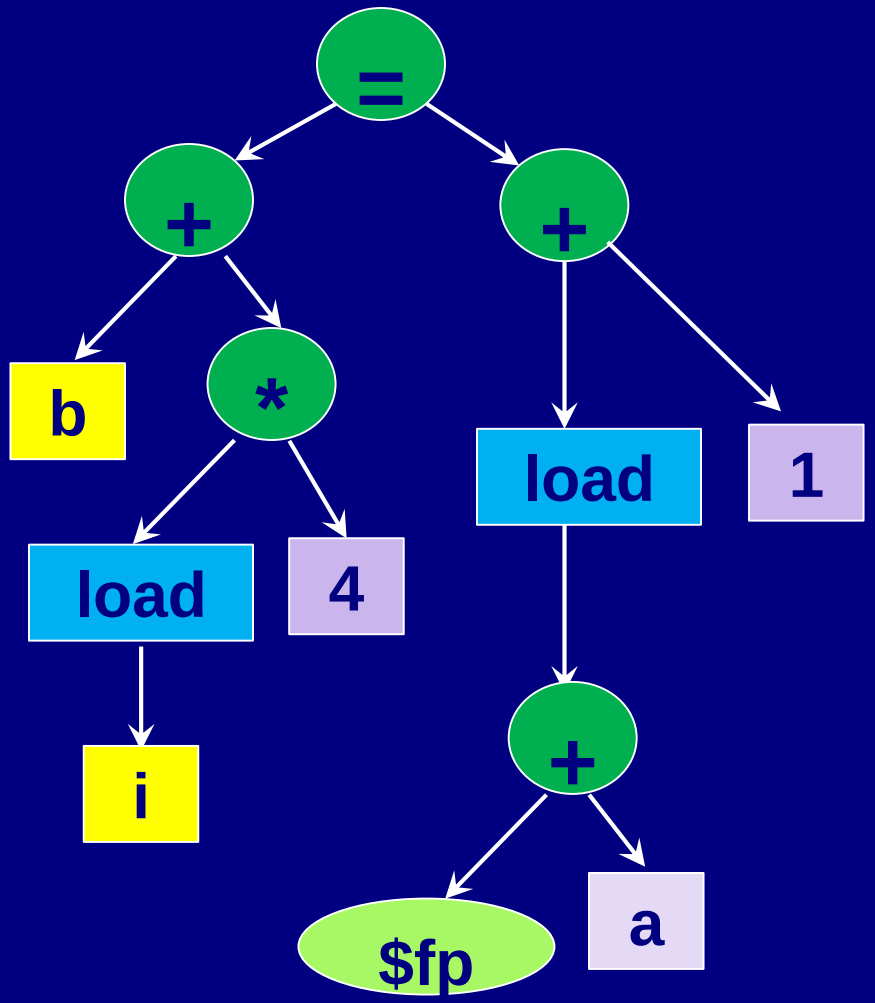
Automatic Instruction Selection

- Instruction selection
  - Relatively easy for RISC machines
  - Complex for CISC machines
    - Wide variety of addressing modes, operands do not need to be in registers, … etc
  - A challenge to retargetable compilers
- Idea:
  - Generate source code into a low level IR code sequence (down to register level), represented as trees
  - Each target machine instruction is also represented as an individual subtree
  - Code generation turns into a tree matching problem like parsing

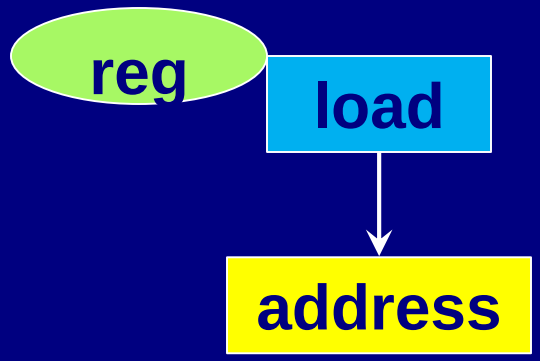
Automatic Instruction Selection

- Example b[i] = a + 1

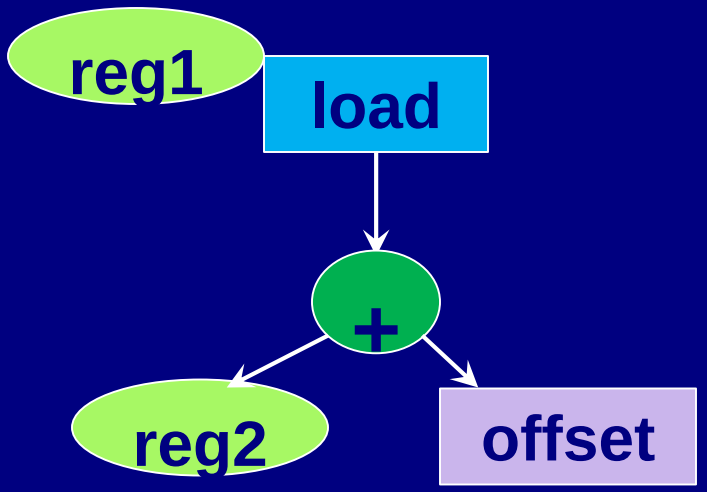
Low level IR tree



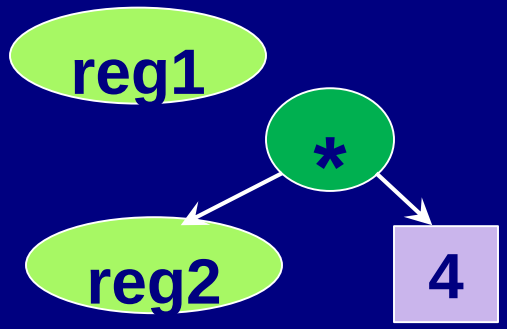
IR Tree Patterns for MIPS Instructions



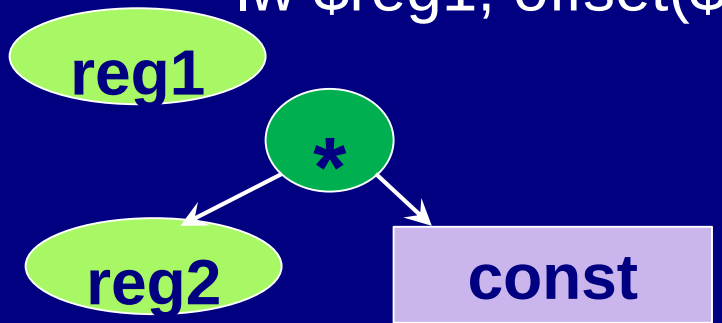
lw $reg, address



lw $reg1, offset($reg2)

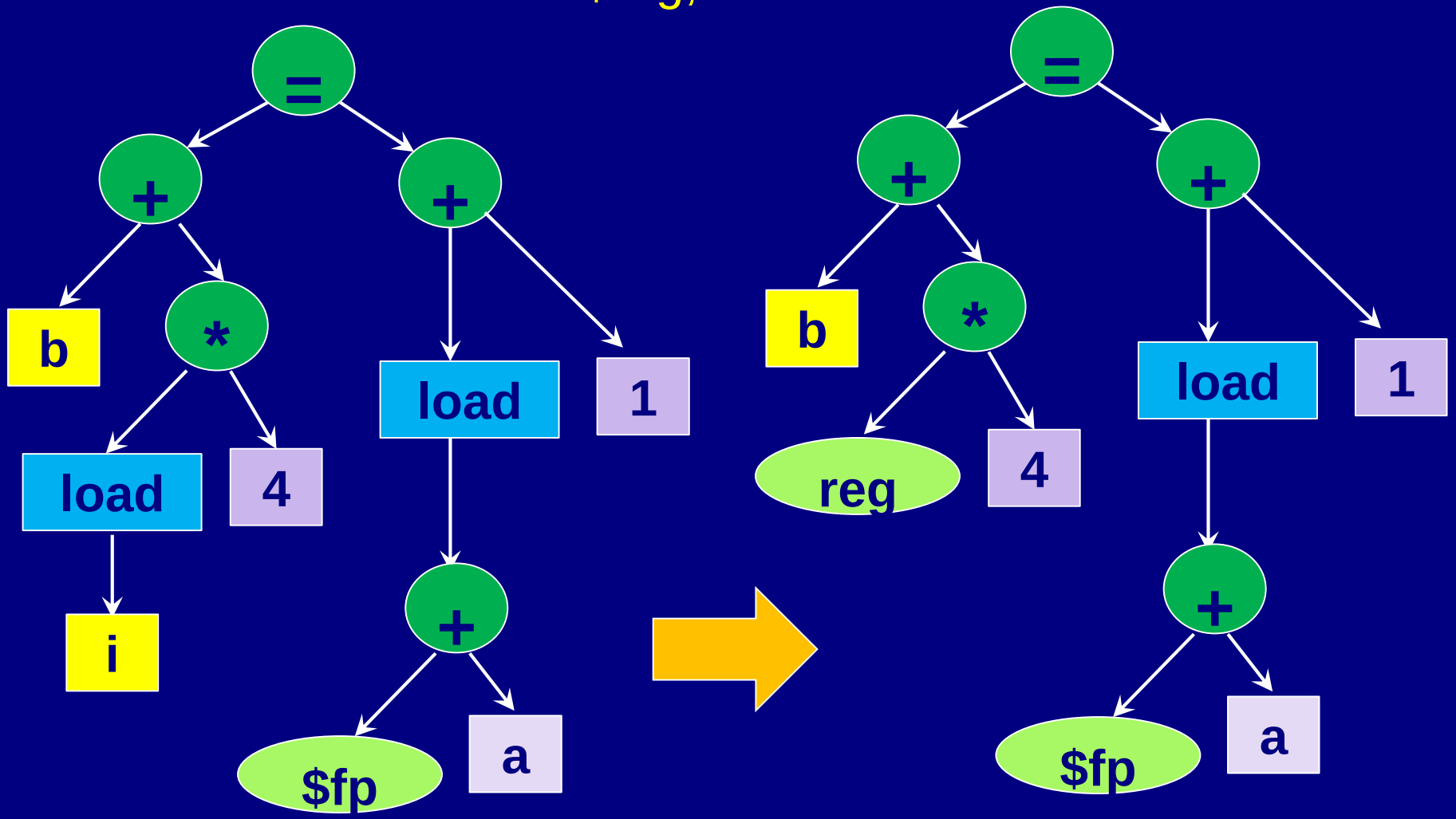


sll $reg1, $reg2, 2



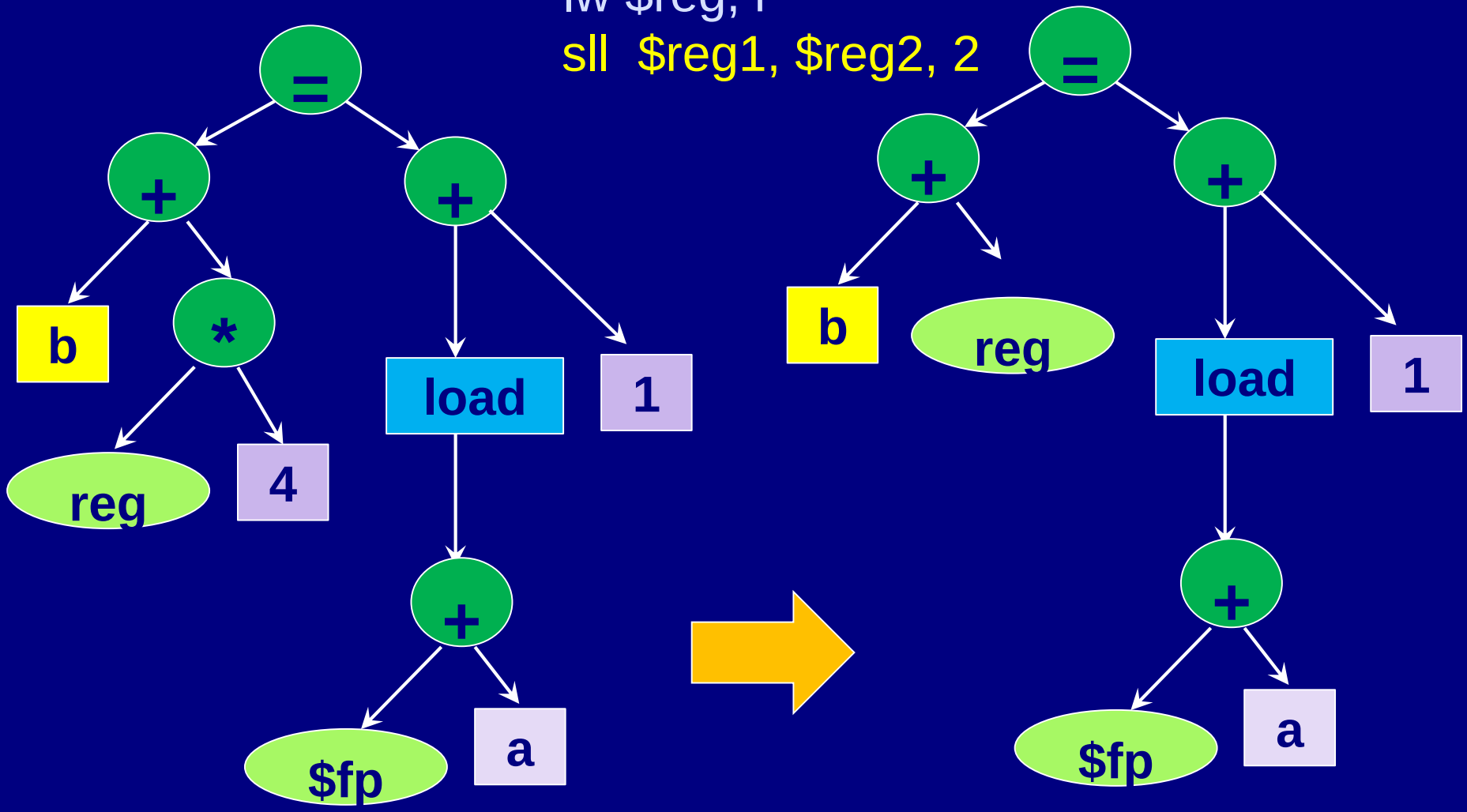
mul $reg1, $reg2, const

lw $reg, i



Similar to bottom-up parsing

lw $reg, i
sll $reg1, $reg2, 2



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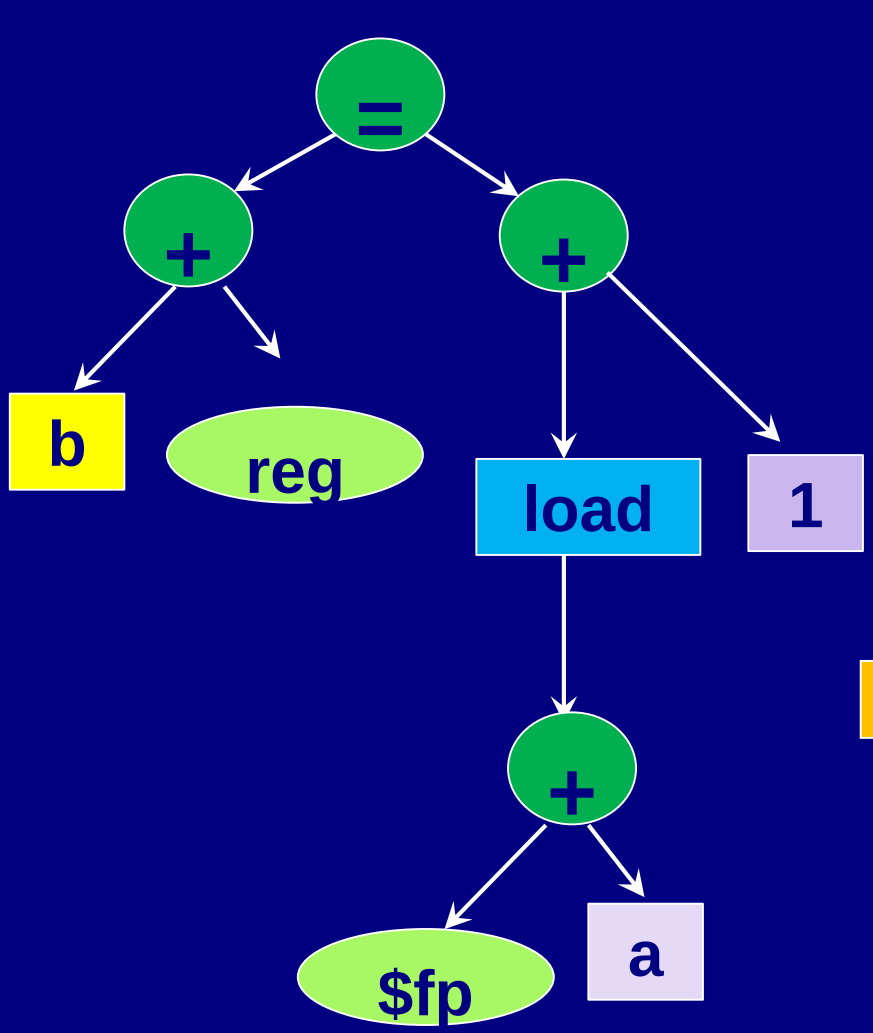
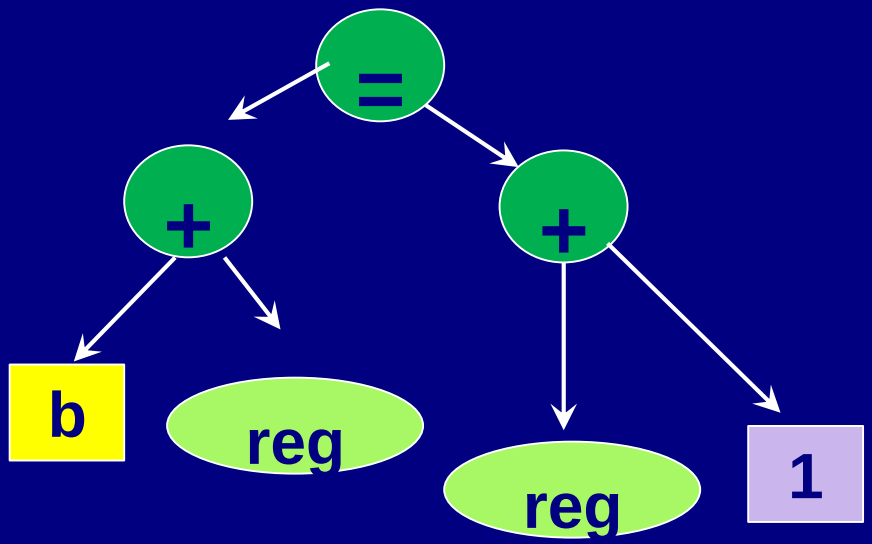
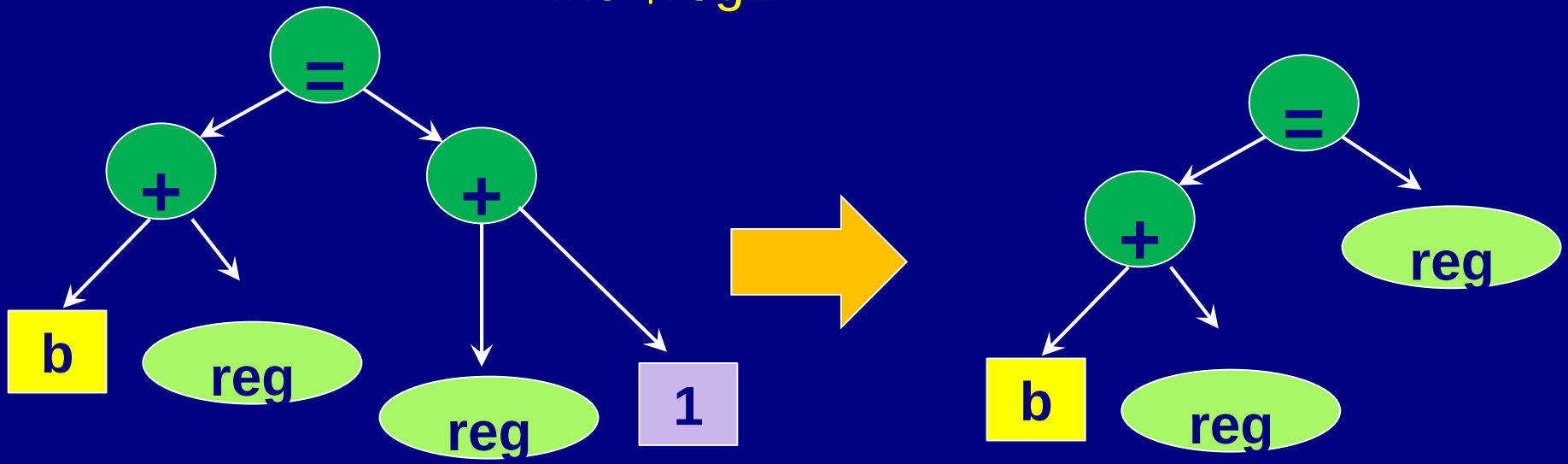





```
lw $reg, i
sll  $reg1, $reg2, 2
lw $reg1, offset($reg2)
```

Similar to bottom-up parsing

lw $reg, i
sll $reg1, $reg2, 2
lw $reg3, offset($reg4)
inc $reg1



Similar to bottom-up parsing

Search for Least-Cost Tree Pattern

- More than one instruction sequence can implement the same construct.
  - In terms of IR trees, different reductions of the same tree yielding different code sequences.
  - So how do we obtain the least expensive code sequence?
- Both BURS (Bottom-Up Rewriting System) and TWIG use dynamic programming to find the least cost cover for a subtree. (see textbook chapter 13.5)