Compiler Construction

Lecture 19: Code Generation V (Compiler Backend)

Winter Semester 2018/19

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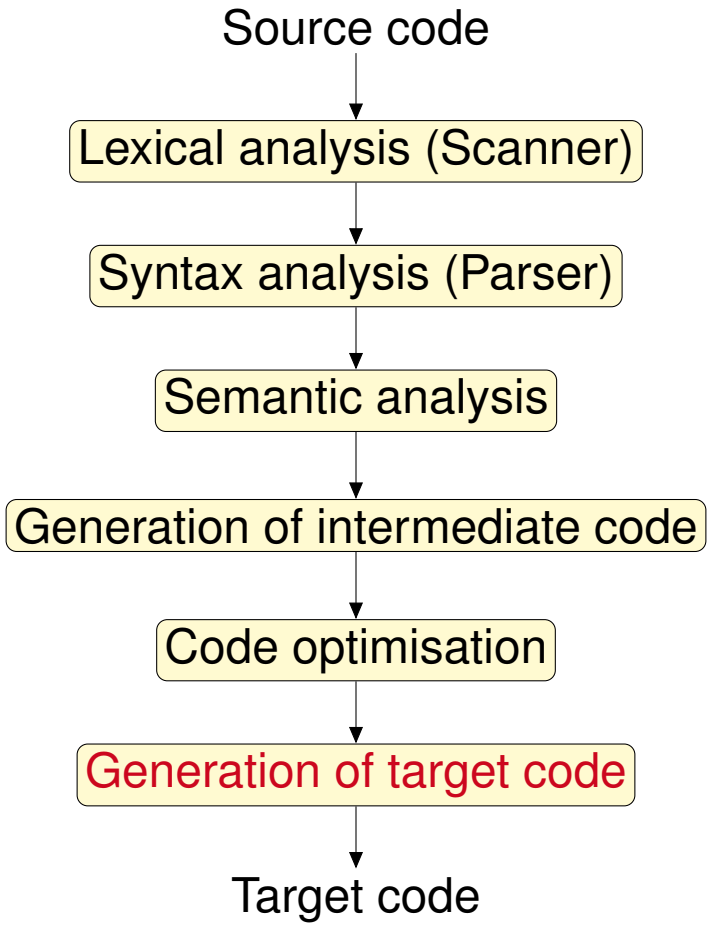
`https://moves.rwth-aachen.de/teaching/ws-1819/cc/`

Software Modeling and Verification Chair
RWTH AACHEN UNIVERSITY

Outline of Lecture 19

Conceptual Structure of a Compiler



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- registers (program counter, data [universal/floating point/address], frame pointer, index register, condition code, ...)
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- main memory (“slow” RAM)
- background storage (disks, sticks, ...)

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Instructions: select adequately (number/type of operands, addressing modes, ...)

Code Generation Phases

1. Register allocation: registers used for
   - values of (frequently used) variables and intermediate results
   - computing memory addresses (array indexing, ...)
   - passing parameters to procedures/functions
2. Instruction selection:
   - translation of abstract instructions into (sequences of) real instructions
   - employ special instructions for efficiency (e.g., `INC(x)` rather than `ADD(x,1)`)
3. Instruction scheduling (placement): increase level of parallelism and/or pipelining by smart ordering of instructions

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Instruction sequence ($r = 2$):

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Shorter sequence:

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- How to compute systematically?
- **Idea:** start with register-intensive subexpressions

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    1. evaluate e_2 (using r_2 registers)
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  - if $r_2 < r_1 \leq r$, then e can be evaluated using r_1 registers (symmetrically)
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- The corresponding optimisation algorithm works in two phases:
  1. Marking phase (computes r_i values)
  2. Generation phase (produces actual code)

  (cf. Wilhelm/Maurer: *Übersetzerbau, 2. Auflage*, Springer, 1997, Sct. 12.4)

The Marking Phase

Algorithm 19.2 (Marking phase)

Input: *expression*
(with binary operators op and variables x)

Procedure: *recursively compute*

$$r(x) := \begin{cases} 1 & \text{if } x \text{ is a “left leaf”} \\ 0 & \text{if } x \text{ is a “right leaf”} \\ 1 & \text{if } x \text{ is at the root} \end{cases}$$

$$r(e_1 \; op \; e_2) := \begin{cases} \max\{r(e_1), r(e_2)\} & \text{if } r(e_1) \neq r(e_2) \\ r(e_1) + 1 & \text{if } r(e_1) = r(e_2) \end{cases}$$

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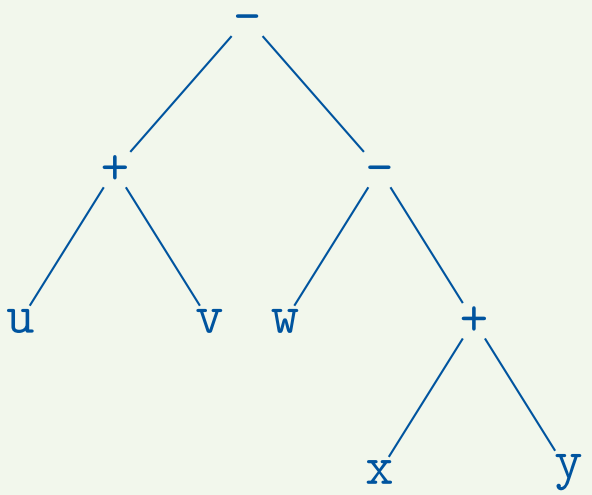

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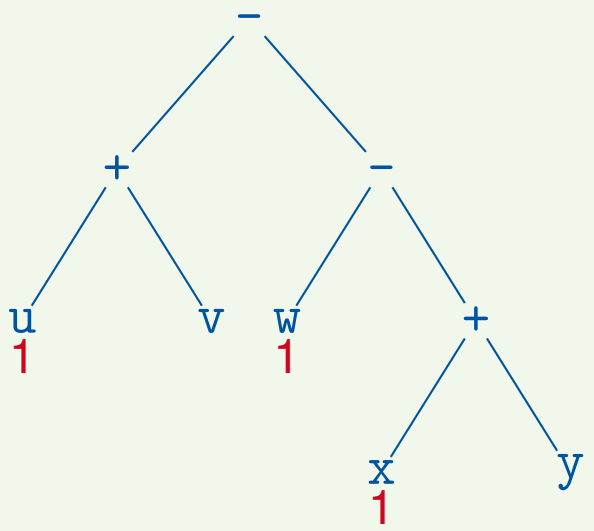

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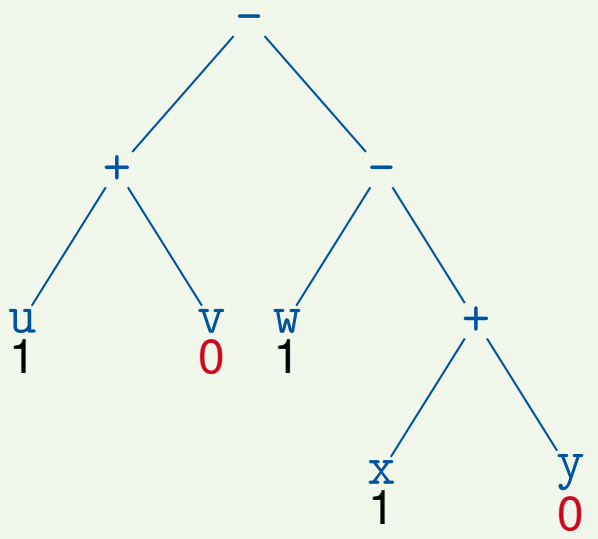

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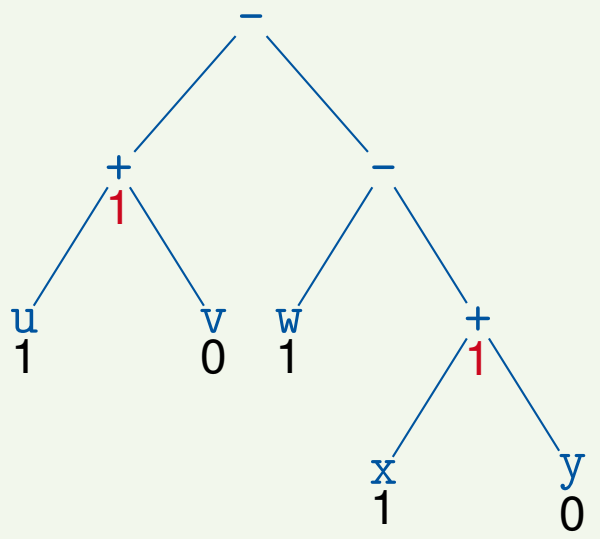

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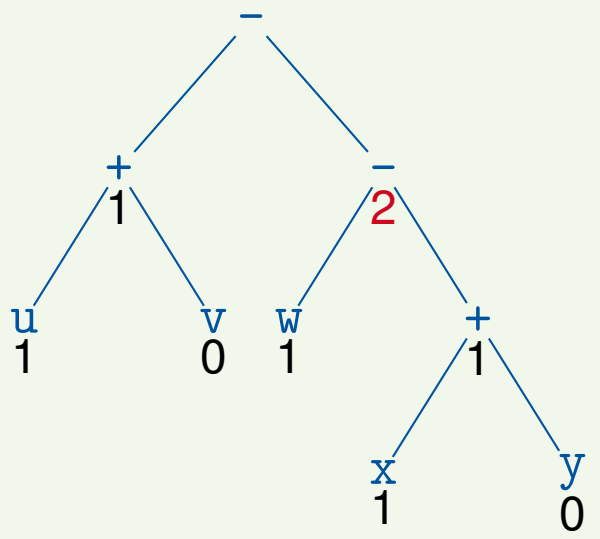

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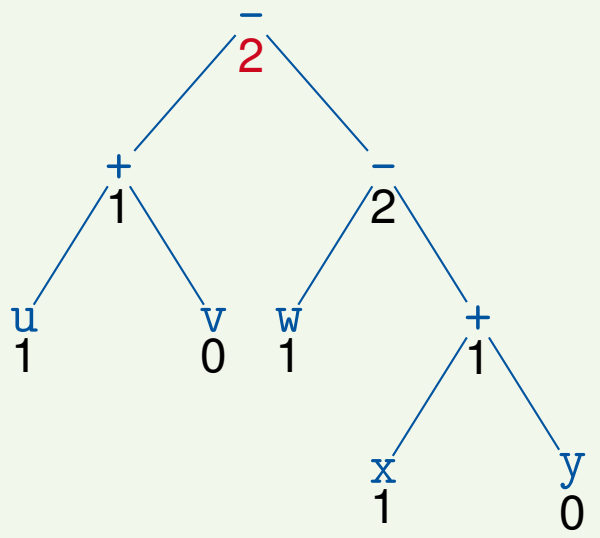

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- Data structures used in Algorithm 19.4:
  - RS: stack of available registers (initially: all r registers; never empty)
  - CS: stack of available main memory cells
- Auxiliary procedures used in Algorithm 19.4:
  - *output*: outputs the argument as code
  - *top*: returns the topmost entry of a stack S (leaving S unchanged)
  - *pop*: removes and returns the topmost entry of a stack
  - *push*: puts an element onto a stack
  - *exchange*: exchanges the two topmost elements of a stack (for preserving argument order in binary operations)

The Generation Phase II

Algorithm 19.4 (Generation phase)

Input: total register numer r; expression e, annotated with register requirement $r(e)$

Variables: RS: stack of registers; CS: stack of memory cells; R: register; C: memory cell;

Procedure: recursive execution of procedure $code(e)$, defined by $code(e) :=$

(1) if $e = x$, $r(x) = 1$: % left leaf
  $output(top(RS) := \texttt{M[}x\texttt{]})$

(2) if $e = e_1$ op y, $r(y) = 0$: % right leaf
  $code(e_1)$;
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(3) if $e = e_1$ op e_2, $r(e_1) < r(e_2)$, $r(e_1) < r$:
  $exchange(RS)$;
  $code(e_2)$;
  $R := pop(RS)$;
  $code(e_1)$;
  $output(top(RS) := top(RS)\ op\ R)$;
  $push(RS, R)$;
  $exchange(RS)$

(4) if $e = e_1$ op e_2, $r(e_1) \geq r(e_2)$, $r(e_2) < r$:
  $code(e_1)$;
  $R := pop(RS)$;
  $code(e_2)$;
  $output(R := R\ op\ top(RS))$;
  $push(RS, R)$

(5) if $e = e_1$ op e_2, $r(e_1) \geq r$, $r(e_2) \geq r$:
  $code(e_2)$;
  $C := pop(CS)$;
  $output(\texttt{M[}C\texttt{]} := top(RS))$;
  $code(e_1)$;
  $output(top(RS) := top(RS)\ op\ \texttt{M[}C\texttt{]})$;
  $push(CS, C)$

Output: optimal (= shortest) code for evaluating e

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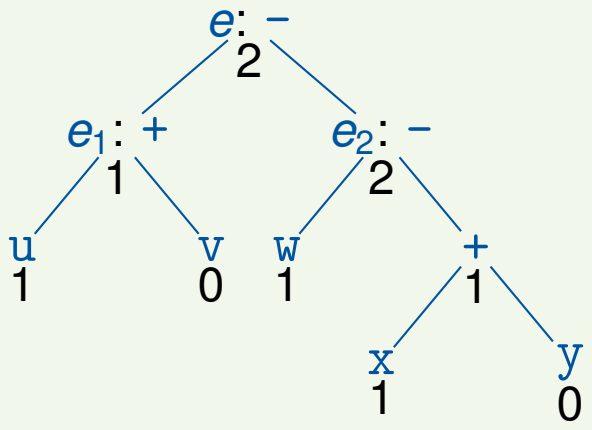

Application of Algorithm 19.4:
on the board

Register Allocation by Graph Colouring I

- Algorithm 19.4: register allocation for single expressions
- Required: global allocation within program/procedure body
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1. Use unbounded number of symbolic registers for storing intermediate values
2. Consider life span of symbolic registers: r is live at program point p if
   - there is a path to p on which r is set and
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3. Life span of r = program points where r is live

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- Approach: graph colouring

Register allocation by graph colouring

1. Use unbounded number of symbolic registers for storing intermediate values
2. Consider life span of symbolic registers: r is live at program point p if
   - there is a path to p on which r is set and
   - there is a path from p on which r is read before being set
3. Life span of r = program points where r is live
4. Two registers are in interference if their life spans intersect

Register Allocation by Graph Colouring I

- Algorithm 19.4: register allocation for single expressions
- Required: global allocation within program/procedure body
- Approach: graph colouring

Register allocation by graph colouring

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5. Yields register interference graph (nodes = life spans, edges = interferences)

Register Allocation by Graph Colouring I

- Algorithm 19.4: register allocation for single expressions
- Required: global allocation within program/procedure body
- Approach: graph colouring

Register allocation by graph colouring

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   - there is a path to p on which r is set and
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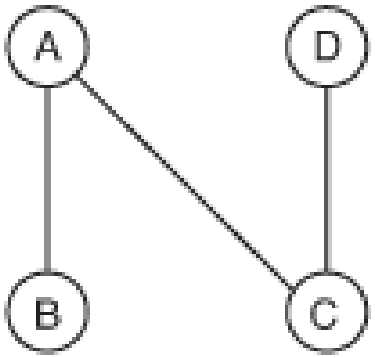
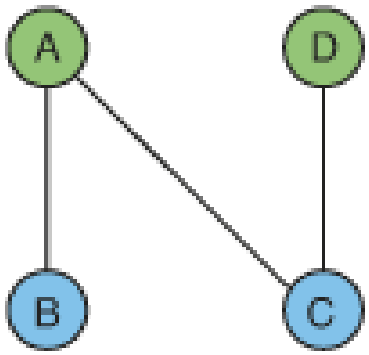
3. Life span of r = program points where r is live
4. Two registers are in interference if their life spans intersect
5. Yields register interference graph (nodes = life spans, edges = interferences)
6. Program executable with k real registers iff interference graph k-colourable

Register Allocation by Graph Colouring II

Example 19.6

Code Sequence	Interference Graph	Colored Graph	Final Allocation
A = … B = … … B … C = … … A … D = … … D … … C …			R1 = … R2 = … … R2 … R2 = … … R1 … R1 = … … R1 … … R2 …

Outline of Lecture 19

Further Topics in Compiler Construction

- Translation of higher-level constructs (modules, classes, ...)
- Translation of non-procedural languages
  - object-oriented (inheritance, polymorphism, dynamic dispatch, ..)
  - functional (higher-order functions, type checking/inference, lazy evaluation, ...)
  - logical (unification, resolution, backtracking, ...)
- Symbol-table handling
- Error handling (detection & recovery)
- Bootstrapping
- Compiler verification
  - *Semantics and Verification of Software* in Summer 2019
- Code optimisation (on source/intermediate/machine code level)
  - *Static Program Analysis* in Winter 2019/20

Outlook

Exams

Exams

1. Thursday, 21 February, 10:00–12:00, AH 1/4/5, Aula 2 (location subject to change)
2. Monday, 25 March, 10:00–12:00, AH 4/5 (location subject to change)

Outlook

Courses & Seminars

Summer 2019: Course *Semantics and Verification of Software* [Noll]

- Operational semantics
- Denotational semantics
- Axiomatic semantics
- Semantic equivalence
- Compiler correctness

Outlook

Courses & Seminars

Summer 2019: Course *Semantics and Verification of Software* [Noll]

- Operational semantics
- Denotational semantics
- Axiomatic semantics
- Semantic equivalence
- Compiler correctness

Summer 2019: Seminar *Program Synthesis* [Noll et al.]

Goal: automatically finding a program (of the underlying programming language) that satisfies a user-given specification

- Enumerative search
- Constraint Solving
- Stochastic Search
- Programming by Examples
- Applications

Companion seminar: *Foundations of Probabilistic Programming* [Katoen et al.]

Outline of Lecture 19

Nichts spezielles,
aber insgesamt gut :)

5.2 What did you **dislike** about the lecture?

Die Vorlesung ist in der PO als 3SWS
gelistet, wurde aber vierstündig gehalten.
Das finde ich vom Inhalt ok, aber
vielleicht sollte sich das Modul
"offiziell" auf 4 SWS ändern

Das Beispiel für EPL hätt ausführlicher sein können. Insbesondere wie die Stacks aussehen nach operationen

The explanation for cycle checking was quite kryptic in the Handout.

the lecture is super notation-heavy. Maybe something as simple as a "notation cheat sheet" with some examples could help a lot.

- Manchmal eine lange, langweilige Abfolge von Notationen und Definitionen, bis man zu einem Ergebnis kommt

- Slides would be easier to understand with (additional) informal explanations

Aus irgendeinem Grund, den ich per se jetzt nicht feststellen kann, lässt meine Konzentration in CC überproportional schnell nach.

Sometimes too much focus on detail

Nice

You can't see on the website when lecture slides are updated

- The slides (especially definitions) are sometimes not very clean (For example: implicit notations)

- I would like to have more examples in the slides

- slides are sometimes too 'mathematical'; some intuition / more examples on the slides would be nice

It is often difficult to get an overview about all definitions.
↳ sometimes not easy to understand

slides are sometimes hard to understand when re-looking at them without explanation

1. Don't provide pseudo code for example for LR(0), LR(1) SLR algorithms, or tell us the implementation idea of them (using stack.)
2. by applying which data-structure we can implement symbol table etc..
3. some symbols not uniquely defined.

~~Ende~~

some slides are
overloaded with content
(e.g. examples).

Es wird den Dozenten
nicht erlaubt seine
Vorlesung in Ruhe zu
beenden. Sobald
das Ende absehbar
ist, ~~ist~~ sehr viel
Gerascheln hörbar.

Der Dozent könnte
ab und zu um Ruhe
bitten.