Compilerbau

Martin Plümicke

WS 2018/19

Agenda

I. Überblick Vorlesung
  Literatur

II. Compiler Überblick

III. Überblick Funktionale Programmierung
  Einleitung
  Haskell-Grundlagen

IV. Compiler
  Scanner

Literatur

- Bauer and Höllerer.
  Übersetzung objektorientierter Programmiersprachen.
  Springer-Verlag, 1998, (in german).
- Alfred V. Aho, Ravi Lam, Monica S.and Sethi, and Jeffrey D. Ullman.
  Compiler: Prinzipien, Techniken und Werkzeuge.
  Pearson Studium Informatik. Pearson Education Deutschland, 2. edition, 2008.
  (in german).
- Alfred V. Aho, Ravi Sethi, and Jeffrey D. Ullman.
  Compilers Principles, Techniques and Tools.
  Addison Wesley, 1986.
- Reinhard Wilhelm and Dieter Maurer.
  Übersetzerbau.
  Springer-Verlag, 2. edition, 1992.
  (in german).

Literatur II

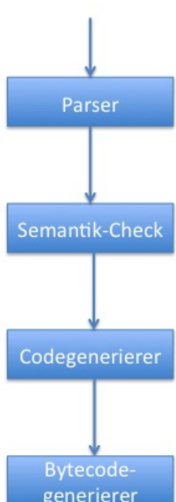
James Gosling, Bill Joy, Guy Steele, Gilad Bracha, and Alex Buckley.
The Java® Language Specification.
The Java series. Addison-Wesley, Java SE 8 edition, 2014.

Tim Lindholm, Frank Yellin, Gilad Bracha, and Alex Buckley.
The Java® Virtual Machine Specification.
The Java series. Addison-Wesley, Java SE 8 edition, 2014.

Bryan O'Sullivan, Donald Bruce Stewart, and John Goerzen.
Real World Haskell.
O'Reilly, 2009.

Peter Thiemann.
Grundlagen der funktionalen Programmierung.
Teubner, 1994.

Compiler Überblick



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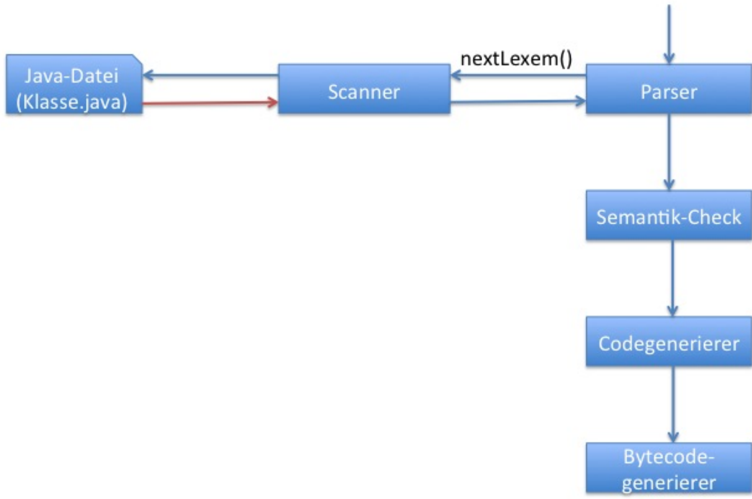

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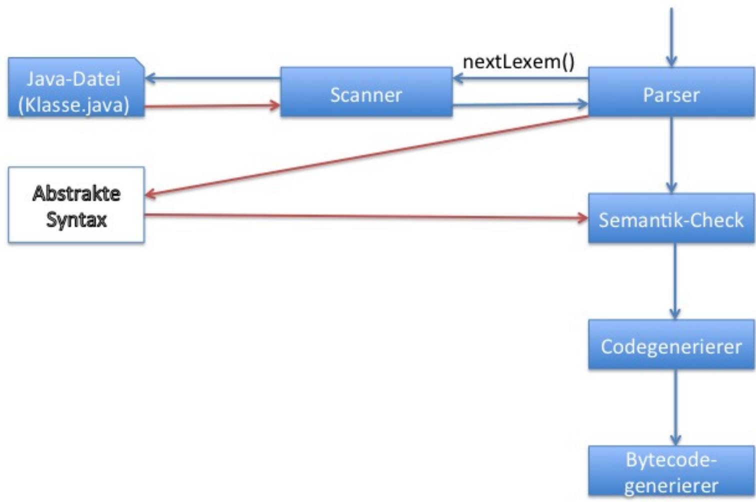

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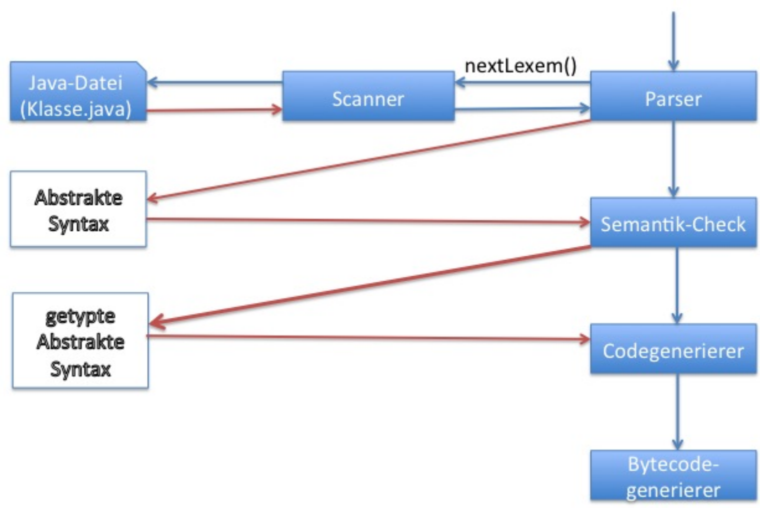

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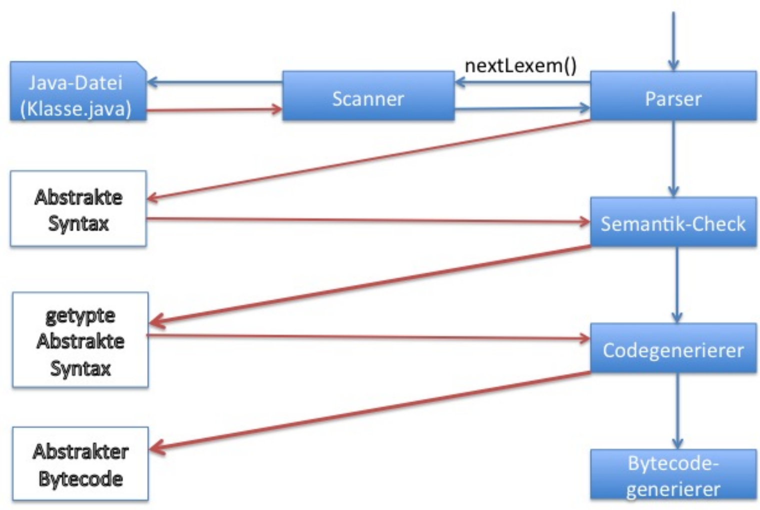

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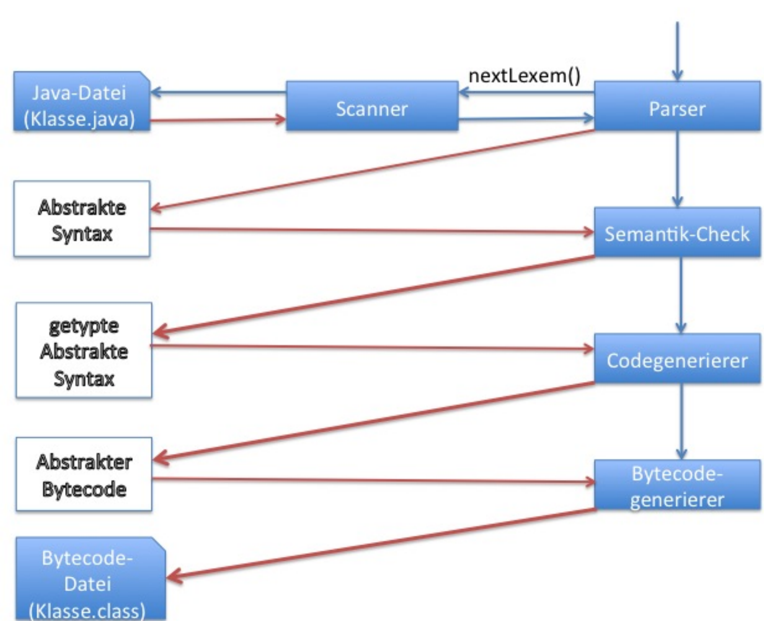
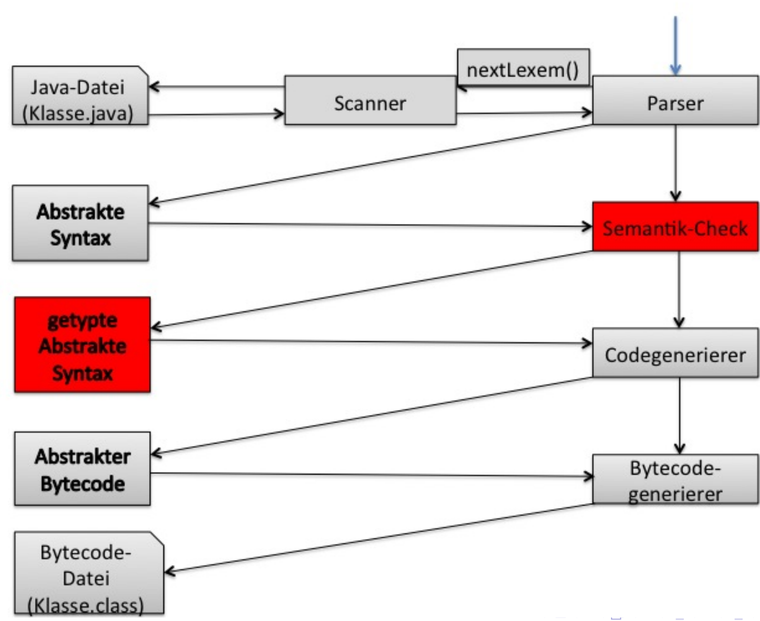


Semantische Analyse/Typecheck



Semantische Analyse/Typecheck

- Überprüfen der Kontextsensitiven Nebenbedingungen:
  - alle Variablen/Methoden deklariert/sichtbar?
  - Typen korrekt?
- Typisierung aller Sub–Terme

Ungetypte abstrakte Syntax für *Mini*–Java I

```
data Class = Class(Type, [FieldDecl], [MethodDecl])

data FieldDecl = FieldDecl(Type, String)

data MethodDecl = Method(Type, String,[(Type,String)], Stmt)

data Stmt = Block([Stmt])
          | Return( Expr )
          | While( Expr , Stmt )
          | LocalVarDecl(Type, String)
          | If(Expr, Stmt , Maybe Stmt)
          | StmtExprStmt(StmtExpr)

data StmtExpr = Assign(String, Expr)
              | New(Type, [Expr])
              | MethodCall(Expr, String, [Expr])
```

Ungetypte abstrakte Syntax für *Mini*–Java II

```
data Expr = This
          | Super
          | LocalOrFieldVar(String)
          | InstVar(Expr, String)
          | Unary(String, Expr)
          | Binary(String, Expr, Expr)
          | Integer(Integer)
          | Bool(Bool)
          | Char(Char)
          | String(String)
          | Jnull
          | StmtExprExpr(StmtExpr)

type Prg = [Class]
```

Formale Definitionen I

Typableitungen

Menge von Typannahmen: $O = \{\, id_1 : ty_1, \ldots, id_n : ty_n \,\}$

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$$O \ \triangleright_{Id} \ id : ty$$

Aus der Menge der Typannahmen O ist für den Bezeichner id der Typ ty ableitbar.

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$$O \ \triangleright_{Stmt} \ s : ty$$

Aus der Menge der Typannahmen O ist für das Statement s der Typ ty ableitbar.

Formale Definitionen II

Typurteile

$$[\textbf{Regelname}] \; \frac{O1 \; \triangleright \; x : ty1}{O2 \; \triangleright \; y : ty2}$$

Aus der Regel *Regelname* folgt, wenn man aus $O1$ ableiten kann, dass x den Typ ty1 hat, dann kann man aus $O2$ ableiten dass y den Typ $ty2$ hat.

Ident–Rule

$$[\textbf{Ident}] \; \frac{(f : ty) \in O_\tau}{O_\tau \; \triangleright_{Id} \; f : ty}$$

O_τ: Menge aller in der Klasse τ sichtbaren Methoden und Attribute

Beispiel Ident–Rule

```
class A {
    Integer attr;
    A meth(Boolean x) { ... }
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$$[\textbf{Ident}]\ \frac{O_{\mathtt{A}}}{O_{\mathtt{A}}\ \triangleright_{Id}\ \mathtt{attr} : \mathtt{Integer}}$$

Beispiel Ident–Rule

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class A {
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$$[\textbf{Ident}]\ \frac{O_{\mathtt{A}}}{O_{\mathtt{A}}\ \rhd_{Id}\ \mathtt{attr} : \mathtt{Integer}}$$

$$[\textbf{Ident}]\ \frac{O_{\mathtt{A}}}{O_{\mathtt{A}}\ \rhd_{Id}\ \mathtt{meth} : \mathtt{Boolean} \rightarrow \mathtt{A}}$$

Literal–Regeln

$$[\textbf{IntLiteral}] \quad O \triangleright_{Expr} \mathsf{Int}(\, n\,) : \texttt{int}$$

$$[\textbf{BoolLiteral}] \quad O \triangleright_{Expr} \mathsf{Bool}(\, b\,) : \texttt{boolean}$$

$$[\textbf{CharLiteral}] \quad O \triangleright_{Expr} \mathsf{Char}(\, c\,) : \texttt{char}$$

$$[\textbf{NullLiteral}] \quad O \triangleright_{Expr} \mathsf{Null} : \theta'$$

Expression–Regel: Simple–Expressions

$$[\textbf{Unary1}] \quad \frac{O \ \triangleright_{Expr} \ e : \texttt{int}}{O \ \triangleright_{Expr} \ \text{Unary}(\text{"+"} / \text{"-"}, e) : \texttt{int}}$$

Expression–Regel: Simple–Expressions

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$$[\textbf{Unary2}]\quad \frac{O \ \triangleright_{Expr} \ e : \texttt{boolean}}{O \ \triangleright_{Expr} \ \text{Unary}(\text{"!"}, e) : \texttt{boolean}}$$

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$$[\textbf{Unary1}]\ \frac{O \ \triangleright_{Expr}\ e : \texttt{int}}{O \ \triangleright_{Expr}\ \text{Unary}(\text{"+"}/\text{"-"}, e) : \texttt{int}}$$

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$$[\textbf{Binary1}]\ \frac{O \ \triangleright_{Expr}\ e1 : \texttt{int}, O \ \triangleright_{Expr}\ e2 : \texttt{int}}{O \ \triangleright_{Expr}\ \text{Binary}(\text{"+"}/\text{"-"}/\text{"*"}/\text{"\%"}, e1, e2) : \texttt{int}}$$

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$$[\textbf{Unary1}]\ \frac{O\ \triangleright_{Expr}\ e : \texttt{int}}{O\ \triangleright_{Expr}\ \text{Unary}(\text{"+"}/\text{"-"}, e) : \texttt{int}}$$

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$$[\textbf{Binary2}]\ \frac{O\ \triangleright_{Expr}\ e1 : \texttt{boolean},\ O\ \triangleright_{Expr}\ e2 : \texttt{boolean}}{O\ \triangleright_{Expr}\ \text{Binary}(\text{"\&\&"}/\text{"||"}, e1, e2) : \texttt{boolean}}$$

Expression–Regel: Variablen

$$[\textbf{LocalOrFieldVar}] \quad \frac{O \;\triangleright_{Id}\; v : \theta}{O \;\triangleright_{Expr}\; \mathrm{LocalOrFieldVar}(\, v \,) : \theta}$$

Expression–Regel: Variablen

$$[\textbf{LocalOrFieldVar}] \quad \frac{O \;\triangleright_{Id}\; v : \theta}{O \;\triangleright_{Expr}\; \text{LocalOrFieldVar}(\, v\,) : \theta}$$

$$[\textbf{InstVar}] \quad \frac{O \;\triangleright_{Expr}\; re : \overline{\tau}, \qquad O_{\overline{\tau}} \;\triangleright_{Id}\; v : \theta}{O \;\triangleright_{Expr}\; \text{InstVar}(\, re, v\,) : \theta}$$

Beispiel `InstVar`

```
class A {
    Integer attr;
    A meth(Boolean x) { ... }
}
```

$O_{\mathtt{A}} = \{\, \mathtt{attr} : \mathtt{Integer},\ \mathtt{meth} : \mathtt{Boolean} \rightarrow \mathtt{A} \,\}$

```
...
A a = new A()
a.attr = 5;
```

übersetzt in abstrakte syntax: **InstVar**(LocalOrFieldVar(*a*), *attr*).

Beispiel InstVar

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class A {
    Integer attr;
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$$[\textbf{Ident}]\ \frac{\{\, a : A \,\}}{\{\, a : A \,\} \rhd_{Id}\ \mathtt{a} : \mathtt{A}}$$

$$[\textbf{LocalOrFieldVar}]\ \frac{\{\, a : A \,\} \rhd_{Id}\ \mathtt{a} : \mathtt{A}}{\{\, a : A \,\} \rhd_{Expr}\ \text{LocalOrFieldVar}(\, a \,) : \mathtt{A}}$$

$$\frac{O_{\mathtt{A}}}{\quad}$$

Beispiel `InstVar`

```
class A {
    Integer attr;
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$$\dfrac{[\textbf{Ident}]\ \dfrac{\{\, a : A \,\}}{\{\, a : A \,\} \rhd_{Id}\ \mathtt{a} : \mathtt{A}}}{[\textbf{LocalOrFieldVar}]\ \{\, a : A \,\} \rhd_{Expr}\ \text{LocalOrFieldVar}(\, a\,) : \mathtt{A},} \quad [\textbf{Ident}]\ \dfrac{O_{\mathtt{A}}}{O_{\mathtt{A}} \rhd_{Id}\ \mathtt{attr} : \mathtt{Integer}}$$

$$[\textbf{InstVar}]\ \overline{\{\, a : A \,\} \rhd_{Expr}\ \textbf{InstVar}(\, \text{LocalOrFieldVar}(\, a\,), attr\,) : \mathtt{Integer}}$$

Expression–Regel: Statement–Expressions

[**New**] $\quad O \ \triangleright_{Expr} \ \mathrm{New}(\,\theta\,) : \theta$

[1] $\leq^*$ ist die Subtypen–Relation

Expression–Regel: Statement–Expressions

[New] $\quad O \ \rhd_{Expr} \ \text{New}(\ \theta\ ) : \theta$

[Assign] $\quad \dfrac{O \ \rhd_{Expr} \ ve : \theta', O \ \rhd_{Expr} \ e : \theta}{O \ \rhd_{Expr} \ \text{Assign}(\ ve, e\ ) : \theta'} \ \theta \leq^* \theta'$[1]

[1] $\leq^*$ ist die Subtypen–Relation

Expression–Regel: Statement–Expressions

[New] $O \ \triangleright_{Expr} \ \mathrm{New}(\, \theta \,) : \theta$

[Assign]
$$\frac{O \ \triangleright_{Expr} \ ve : \theta',\ O \ \triangleright_{Expr} \ e : \theta}{O \ \triangleright_{Expr} \ \mathrm{Assign}(\, ve, e \,) : \theta'} \quad \theta \leq^* \theta'^{1}$$

[Method-Call]
$$\frac{\begin{array}{c} O \ \triangleright_{Expr} \ re : \overline{\tau} \\ O_{\overline{\tau}} \ \triangleright_{Id} \ m : \theta'_1 \times \ldots \times \theta'_n \rightarrow \theta \\ \forall 1 \leqslant i \leqslant n : \ O \ \triangleright_{Expr} \ e_i : \theta_i \end{array}}{O \ \triangleright_{Expr} \ \mathrm{MethodCall}(\, re, m, (e_1, \ldots, e_n) \,) : \theta} \quad \theta_i \leq^* \theta'_i$$

[1] $\leq^*$ ist die Subtypen–Relation

Beispiel MethodCall

```
class A {
    Integer attr;
    A meth(Boolean x) { ... }
}
```

$O_{\mathtt{A}} = \{\, \mathtt{attr} : \mathtt{Integer},\ \mathtt{meth} : \mathtt{Boolean} \to \mathtt{A} \,\}$

```
...
A a = new A()
A aa = a.meth(true);
```

übers. in abstrakte Syntax:

MethodCall(**LocalOrFieldVar**(*a*), *meth*, Bool(`true`)).

Beispiel MethodCall

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    Integer attr;
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$$[\textbf{LocalOrFieldVar}] \frac{[\textbf{Ident}] \dfrac{\{ a : A \}}{\{ a : A \} \rhd_{Id} \ \mathtt{a} : \mathtt{A}}}{\{ a : A \} \rhd_{Expr} \ \mathrm{LocalOrFieldVar}(a) : \mathtt{A}}$$

$$\frac{O_{\mathtt{A}}}{\quad}$$

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$$[\textbf{Ident}]\ \dfrac{\{\, a : A \,\}}{\{\, a : A \,\} \rhd_{Id}\ \mathtt{a} : \mathtt{A}}$$

$$[\textbf{LocalOrFieldVar}]\ \dfrac{\{\, a : A \,\} \rhd_{Id}\ \mathtt{a} : \mathtt{A}}{\{\, a : A \,\} \rhd_{Expr}\ \mathrm{LocalOrFieldVar}(\, a \,) : \mathtt{A},}$$

$$[\textbf{Ident}]\ \dfrac{O_{\mathtt{A}}}{O_{\mathtt{A}} \rhd_{Id}\ \mathtt{meth} : \mathtt{Boolean} \to \mathtt{A}}$$

Beispiel MethodCall

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$O_A = \{ \texttt{attr} : \texttt{Integer}, \ \texttt{meth} : \texttt{Boolean} \rightarrow \texttt{A} \}$

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übers. in abstrakte Syntax:

$$\textbf{MethodCall}(\ \textbf{LocalOrFieldVar}(\ a\ ),\ \mathit{meth},\ \text{Bool}(\ \texttt{true}\ )\ ).$$

$$[\textbf{LocalOrFieldVar}]\ \dfrac{[\textbf{Ident}]\ \dfrac{\{\ a : A\ \}}{\{\ a : A\ \} \rhd_{Id}\ \texttt{a} : \texttt{A}}}{\{\ a : A\ \} \rhd_{Expr}\ \text{LocalOrFieldVar}(\ a\ ) : \texttt{A},}$$

$$[\textbf{Ident}]\ \dfrac{O_A}{O_A \rhd_{Id}\ \texttt{meth} : \texttt{Boolean} \rightarrow \texttt{A}}$$

$$[\textbf{BoolLiteral}]\ \text{Bool}(\ \texttt{true}\ ) : \texttt{boolean}$$

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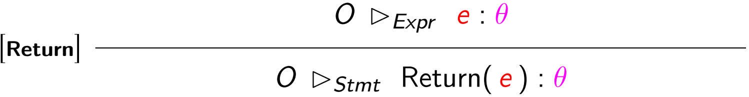
$$\text{[BoolLiteral]}\ \text{Bool}(\, \mathtt{true} \,) : \mathtt{boolean}$$

$$\text{[MethodCall]}\ \frac{\{\, a : A \,\} \rhd_{Expr}\ \text{LocalOrFieldVar}(\, a \,) : \mathtt{A}, \quad O_{\mathtt{A}} \rhd_{Id}\ \mathtt{meth} : \text{Boolean} \rightarrow \mathtt{A}, \quad \text{Bool}(\, \mathtt{true} \,) : \mathtt{boolean}}{\{\, a : A \,\} \rhd_{Expr}\ \textbf{MethodCall}(\, \textbf{LocalOrFieldVar}(\, a \,), \mathtt{meth}, \text{Bool}(\mathtt{true}) \,) : \mathtt{A}}$$

Statement–Regeln



$$[\textbf{Return}]\ \frac{O \ \rhd_{Expr}\ e : \theta}{O \ \rhd_{Stmt}\ \text{Return}(\ e\ ) : \theta}$$

[2] upper bound

Statement–Regeln

$$[\textbf{Return}] \quad \frac{O \ \triangleright_{Expr} \ e : \theta}{O \ \triangleright_{Stmt} \ \text{Return}(\ e\ ) : \theta}$$

$$[\textbf{If}] \quad \frac{\begin{array}{c} O \ \triangleright_{Stmt} \ s_1 : \theta_1, O \ \triangleright_{Stmt} \ s_2 : \theta_2 \\ O \ \triangleright_{Expr} \ e : \texttt{boolean} \end{array}}{O \ \triangleright_{Stmt} \ \text{If}(\ e, s_1, s_2\ ) : \overline{\theta}, \textit{wobei } \overline{\theta} \in \textbf{UB}^2(\ \theta_1, \theta_2\ )}$$

[2] upper bound

Statement–Regeln

$$[\textbf{Return}] \quad \frac{O \ \triangleright_{Expr} \ e : \theta}{O \ \triangleright_{Stmt} \ \text{Return}(\ e\ ) : \theta}$$

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$$[\textbf{While}] \quad \frac{O \ \triangleright_{Expr} \ e : \texttt{boolean}, \ O \ \triangleright_{Stmt} \ \text{Block}(\ B\ ) : \theta}{O \ \triangleright_{Stmt} \ \text{While}(\ e, \text{Block}(\ B\ )\ ) : \theta}$$

[2] upper bound

Statement–Regeln: Statement–Expressions

[**New**] $\qquad O \;\triangleright_{Stmt}\; \mathrm{New}(\,\theta\,) : \texttt{void}$

Statement–Regeln: Statement–Expressions

[New] $\quad O \ \triangleright_{Stmt} \ \text{New}(\ \theta\ ) : \texttt{void}$

[Assign]

$$\frac{O \ \triangleright_{Expr} \ ve : \theta', O \ \triangleright_{Expr} \ e : \theta}{O \ \triangleright_{Stmt} \ \text{Assign}(\ ve, e\ ) : \texttt{void}} \quad \theta \leq^{*} \theta'$$

Statement–Regeln: Statement–Expressions

[New] $O \ \triangleright_{Stmt} \ \text{New}(\,\theta\,) : \texttt{void}$

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$$\frac{O \ \triangleright_{Expr} \ ve : \theta', O \ \triangleright_{Expr} \ e : \theta}{O \ \triangleright_{Stmt} \ \text{Assign}(\,ve, e\,) : \texttt{void}} \quad \theta \leq^* \theta'$$

[Method-Call]

$$\frac{\begin{array}{c} O \ \triangleright_{Expr} \ re : \overline{\tau} \\ O_{\overline{\tau}} \ \triangleright_{Id} \ m : \theta'_1 \times \ldots \times \theta'_n \to \theta \\ \forall 1 \leqslant i \leqslant n : \ O \ \triangleright_{Expr} \ e_i : \theta_i \end{array}}{O \ \triangleright_{Stmt} \ \text{MethodCall}(\,re, m, (e_1, \ldots, e_n)\,) : \texttt{void}} \quad \theta_i \leq^* \theta'_i$$

Block–Statement Regeln

$$[\textbf{BlockInit}] \quad \frac{O \ \rhd_{Stmt} \ stmt : \theta}{O \ \rhd_{Stmt} \ \text{Block}(\ stmt\ ) : \theta}$$

Block–Statement Regeln

[BlockInit]

$$\frac{O \ \triangleright_{Stmt} \ stmt : \theta}{O \ \triangleright_{Stmt} \ \text{Block}(\ stmt\ ) : \theta}$$

[Block]

$$\frac{O \ \triangleright_{Stmt} \ s_1 : \theta, \ \ O \ \triangleright_{Stmt} \ \text{Block}(\ s_2; \ldots; s_n;\ ) : \theta'}{O \ \triangleright_{Stmt} \ \text{Block}(\ s_1; s_2; \ldots; s_n;\ ) : \overline{\theta}, \textit{wobei } \overline{\theta} \in \mathbf{UB}(\ \theta, \theta'\ )}$$

Block–Statement Regeln

[BlockInit]

$$\frac{O \;\triangleright_{Stmt}\; stmt : \theta}{O \;\triangleright_{Stmt}\; \text{Block}(\, stmt \,) : \theta}$$

[Block]

$$\frac{O \;\triangleright_{Stmt}\; s_1 : \theta,\;\; O \;\triangleright_{Stmt}\; \text{Block}(\, s_2; \ldots; s_n; \,) : \theta'}{O \;\triangleright_{Stmt}\; \text{Block}(\, s_1; s_2; \ldots; s_n; \,) : \overline{\theta},\; \textit{wobei}\; \overline{\theta} \in \mathbf{UB}(\, \theta, \theta' \,)}$$

[Blockvoid]

$$\frac{\begin{array}{c} O \;\triangleright_{Stmt}\; s_1 : \texttt{void}, \\ O \;\triangleright_{Stmt}\; \text{Block}(\, s_2; \ldots; s_n; \,) : \theta \end{array}}{O \;\triangleright_{Stmt}\; \text{Block}(\, s_1; s_2; \ldots; s_n; \,) : \theta}$$

Block–Statement Regeln

[BlockInit]

$$\frac{O \ \triangleright_{Stmt} \ stmt : \theta}{O \ \triangleright_{Stmt} \ \mathrm{Block}(\ stmt\ ) : \theta}$$

[Block]

$$\frac{O \ \triangleright_{Stmt} \ s_1 : \theta, \ O \ \triangleright_{Stmt} \ \mathrm{Block}(\ s_2; \ldots; s_n;\ ) : \theta'}{O \ \triangleright_{Stmt} \ \mathrm{Block}(\ s_1; s_2; \ldots; s_n;\ ) : \overline{\theta}, \mathit{wobei}\ \overline{\theta} \in \mathbf{UB}(\ \theta, \theta'\ )}$$

[Blockvoid]

$$\frac{\begin{array}{c} O \ \triangleright_{Stmt} \ s_1 : \mathtt{void}, \\ O \ \triangleright_{Stmt} \ \mathrm{Block}(\ s_2; \ldots; s_n;\ ) : \theta \end{array}}{O \ \triangleright_{Stmt} \ \mathrm{Block}(\ s_1; s_2; \ldots; s_n;\ ) : \theta}$$

[Block-Local-VarDecl]

$$\frac{O \backslash \{\ v : \theta'\ \} \cup \{\ v : \overline{\theta}\ \} \ \triangleright_{Stmt} \ \mathrm{Block}(\ s_2; \ldots; s_n;\ ) : \theta}{O \ \triangleright_{Stmt} \ \mathrm{Block}(\ \mathrm{LocalVarDecl}(\ v, \overline{\theta}\ ); s_2; \ldots; s_n;\ ) : \theta}$$

Beispiel

```
while (true) {
    return 1;
}
```

Beispiel

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$O = \emptyset$

Beispiel

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while (true) {
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}
```

$O = \emptyset$

$$[\textbf{IntLiteral}] \qquad O \rhd_{Expr} \text{Int}(1) : \texttt{int}$$

Beispiel

```
while (true) {
    return 1;
}
```

$O = \emptyset$

$$\textbf{[Return]}\ \frac{\textbf{[IntLiteral]}\ \ O \ \triangleright_{Expr}\ \mathrm{Int}(\,1\,) : \texttt{int}}{O \ \triangleright_{Stmt}\ \mathrm{Return}(\,\mathrm{Int}(\,1\,)\,) : \texttt{int}}$$

Beispiel

```
while (true) {
    return 1;
}
```

$O = \emptyset$

$$\dfrac{\dfrac{[\textbf{IntLiteral}] \quad O \triangleright_{Expr} \text{Int}(1) : \texttt{int}}{O \triangleright_{Stmt} \text{Return}(\text{Int}(1)) : \texttt{int}}\,[\textbf{Return}]}{O \triangleright_{Stmt} \text{Block}(\text{Return}(\text{Int}(1))) : \texttt{int}}\,[\textbf{Block-Init}]$$

Beispiel

```
while (true) {
    return 1;
}
```

$O = \emptyset$

$[\textbf{Bool-Literal}]\; O \rhd_{Expr} \text{Bool}(\,\textit{True}\,) : \texttt{boolean}$

$$
[\textbf{Block-Init}]\;
\dfrac{[\textbf{Return}]\;\dfrac{[\textbf{IntLiteral}]\quad O \rhd_{Expr} \text{Int}(\,1\,) : \texttt{int}}{O \rhd_{Stmt} \text{Return}(\,\text{Int}(\,1\,)\,) : \texttt{int}}}{O \rhd_{Stmt} \text{Block}(\,\text{Return}(\,\text{Int}(\,1\,)\,)\,) : \texttt{int}}
$$

Beispiel

```
while (true) {
    return 1;
}
```

$O = \emptyset$

$$\dfrac{[\textbf{Bool-Literal}]\; O \rhd_{Expr} \text{Bool}(\,\mathit{True}\,) : \texttt{boolean} \qquad [\textbf{Block-Init}]\;\dfrac{[\textbf{Return}]\;\dfrac{[\textbf{IntLiteral}]\; O \rhd_{Expr} \text{Int}(\,1\,) : \texttt{int}}{O \rhd_{Stmt} \text{Return}(\,\text{Int}(\,1\,)\,) : \texttt{int}}}{O \rhd_{Stmt} \text{Block}(\,\text{Return}(\,\text{Int}(\,1\,)\,)\,) : \texttt{int}}}{O \rhd_{Stmt} \text{While}(\,\text{Bool}(\,\mathit{True}\,), \text{Block}(\,\text{Return}(\,\text{Int}(\,1\,)\,)\,)\,) : \texttt{int}}\;[\textbf{while}]$$

Datenstruktur typisierter Expressions

```
type Type = String

-- data Type = TVar(String)          -- Typvariable
--           | TC(String, [Type])    -- Typkonstruktor
--           | WC                    -- Wildscard
--           | WC_Super(Type)        -- Super-Wildscard
--           | WC_Extends(Type)      -- Extends-Wildcard
```

Datenstruktur typisierter Expressions

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type Type = String

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--           | WC_Extends(Type)            -- Extends-Wildcard

data Expr = This
          | Super
          | LocalOrFieldVar(String)
          | InstVar(Expr, String)
          | Unary(String, Expr)
          | Binary(String, Expr, Expr)
          | Integer(Integer)
          | Bool(Bool)
          | Char(Char)
          | String(String)
          | Jnull
          | StmtExprExpr(StmtExpr)
          | TypedExpr(Expr, Type)
```

Datenstruktur typisierter Statements

```
data Stmt = Block([Stmt])
          | Return( Expr )
          | While( Expr , Stmt )
          | LocalVarDecl(String)
          | If(Expr, Stmt , Maybe Stmt)
          | StmtExprStmt(StmtExpr)
          | TypedStmt(Stmt, Type)

data StmtExpr = Assign(String, Expr)
          | New(Type, [Expr])
          | MethodCall(Expr, String, [Expr])
          | TypedStmtExpr(StmtExpr, Type)
```

Typisierung von Simple–Expressions

```
return 1 + 2
```

Erg. der Parsers:

```
Binary("+", Integer(1), Integer(2))
```

Typisierung von Simple–Expressions

```
return 1 + 2
```

Erg. der Parsers:

```
Binary("+", Integer(1), Integer(2))
```

Typisierung:

```
TypedExpr(Binary("+",
                 TypedExpr(Integer(1), "int"),
                 TypedExpr(Integer(2), "int"))
          "int")
```

LocalOrFieldVar

```
class Klassenname {
  int v;
  int methode (int x) {
    return v + x;
  }
}
```

LocalOrFieldVar

```
class Klassenname {
  int v;
  int methode (int x) {
    return v + x;
  }
}
```

Erg. der Parsers:

```
Return(Binary("+",
              LocalOrFieldVar("v")      ← FieldVar
              LocalOrFieldVar("x")))    ← LocalVar
```

LocalOrFieldVar

```
class Klassenname {
  int v;
  int methode (int x) {
    return v + x;
  }
}
```

Erg. der Parsers:

```
Return(Binary("+",
                 LocalOrFieldVar("v")      ← FieldVar
                 LocalOrFieldVar("x")))    ← LocalVar
```

Typisierung:

```
Return(
  TypedExpr(
       Binary("+",
                 TypedExpr(LocalOrFieldVar("v"), "int"),
                 TypedExpr(LocalOrFieldVar("x"), "int")),
        "int"))
```

InstVar, MethodCall

```
class Cl1 {
   char m1 () {
     int b;
     Cl2 x = new Cl2 ()
     return x.m2(x.v, b);
   }
}
```

```
class Cl2 {
  Cl3 v;
  char m2(cl3 v, int w) { ...}
 }

class Cl3 { ...}
```

InstVar, MethodCall

```
class Cl1 {
   char m1 () {
     int b;
     Cl2 x = new Cl2 ()
     return x.m2(x.v, b);
   }
}
```

```
class Cl2 {
  Cl3 v;
  char m2(cl3 v, int w) { ...}
 }

class Cl3 { ...}
```

Erg. der Parsers:

```
Return(MethodCall(LocalOrFieldVar("x"), "m2",
                  [InstVar(LocalOrFieldVar("x"), "v"),
                   LocalOrFieldVar("b")]))
```

InstVar, MethodCall

```
class Cl1 {
   char m1 () {
     int b;
     Cl2 x = new Cl2 ()
     return x.m2(x.v, b);
   }
}
```

```
class Cl2 {
  Cl3 v;
  char m2(cl3 v, int w) { ...}
 }

class Cl3 { ...}
```

Erg. der Parsers:

```
Return(MethodCall(LocalOrFieldVar("x"), "m2",
                  [InstVar(LocalOrFieldVar("x"), "v"),
                   LocalOrFieldVar("b")]))
```

Typisierung:

```
Return(TypedExpr(
  MethodCall(TypedExpr(LocalOrFieldVar("x"), "Cl2"), "m2",
             [TypedExpr(
                InstVar(TypedExpr(LocalOrFieldVar("x"), "Cl2"),
                        "v"), "Cl3"),
              TypedExpr(LocalOrFieldVar("b"), "int")]), "char"))
```

Semantische Analyse/Algorithmus `typecheck`

```
typecheckExpr:: Expr -> [(String, Type)] -> [Class] -> Expr
typecheckStmt:: Stmt -> [(String, Type)] -> [Class] -> Stmt
```

1. Argument: Ungetypter Ausdruck/Statement
2. Argument: Tabelle mit lokalen Variablen, die durch Deklarationen LocalVarDecl verändert werden.
3. Argument: Alle sichtbaren Klassen mit Fields und Methoden

Ergebnis: getypeter Ausdruck/Statement

Semantische Analyse/Algorithmus `typecheck`

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Ergebnis: getypeter Ausdruck/Statement

Ablauf: Lauf über alle Methoden aller Klassen:

- Check ob Variablen/Methoden deklariert
- Check, ob die Typen der Metdodenaufrufe/Zuweisung korrekt sind
- Einfügen der Typisierungen