TECHNISCHE UNIVERSITÄT MÜNCHEN
FAKULTÄT FÜR INFORMATIK

Programming Languages

Metaprogramming

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Winter 2019/20

“Let’s write a program, which writes a program“

Learning outcomes

1. Compilers and Compiler Tools
2. Preprocessors for syntax rewriting
3. Reflection and Metaclasses
4. Metaobject Protocol
5. Macros

Motivation

- Aspect Oriented Programming establishes programmatic refinement of program code
- How about establishing support for program refinement in the language concept itself?
- Treat program <u>code as data</u>

⇝ Metaprogramming

Motivation

- Aspect Oriented Programming establishes programmatic refinement of program code
- How about establishing support for program refinement in the language concept itself?
- Treat program code as data

⇝ Metaprogramming

Metaprogramming

- Treat programs as data
- Read, analyse or transform (other) programs
- Program modifies itself during runtime

Codegeneration Tools

Codegeneration Tools

Compiler Construction

In Compiler Construction, there are a lot of codegeneration tools, that compile DSLs to target source code. Common examples are `lex` and `bison`.

Example: `lex`:
`lex` generates a table lookup based implementation of a finite automaton corresponding to the specified disjunction of regular expressions.

```
%{ #include <stdio.h>
%}
%%          /* Lexical Patterns */
[0-9]+  {   printf("integer: %s\n", yytext); }
.|\n    {   /* ignore           */           }
%%
int main(void) {
    yylex();
    return 0;
}
```

⇝ generates 1.7k lines of C

Codegeneration via Preprocessor

Compiletime-Codegeneration

String Rewriting Systems

A Text Rewriting System provides a set of grammar-like rules (→Macros) which are meant to be applied to the target text.

Example: C Preprocessor (CPP)

```
#define min(X,Y) (( X < Y )? (X) : (Y))
x = min(5,x);      // (( 5 < x )? (5) : (x))
x = min(++x,y+5); // (( ++x < y+5 )? (++x) : (y+5))
```

Compiletime-Codegeneration

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```

⚠ Nesting, Precedence, Binding, Side effects, Recursion, . . .

- Parts of Macro parameters can bind to context operators depending on the precedence and binding behaviour
- Side effects are recomputed for every occurance of the Macro parameter
- Any (indirect) recursive replacement stops the rewriting process
- Name spaces are not separated, identifiers duplicated

Compiletime-Codegeneration

Example application: Language constructs [3]:

```
    ATOMIC (globallock) {
      i--;
      i++;
    }
```

```
#define ATOMIC(lock)    \
  acquire(&lock);\
  { /* user code */ }  \
  release(&lock);
```

⚠ We explicitely want to imitate constructs like while loops, thus we do not want to use round brackets for code block delimiters

Compiletime-Codegeneration

Example application: Language constructs [3]:

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```

⚠ We explicitely want to imitate constructs like while loops, thus we do not want to use round brackets for code block delimiters

⚠ How can we bind the block, following the `ATOMIC` to the usercode fragment?

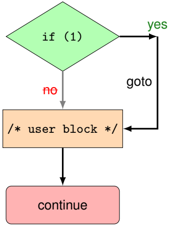
Particularly in a situation like this?

```
  if (i>0)
    ATOMIC (mylock) {
      i--;
      i++;
    }
```

Compiletime-Codegeneration

Prepend code to usercode

```
if (1)
  /* prepended code */
  goto body;
else
   body:
   {/* block following the macro */}
```



Compiletime-Codegeneration

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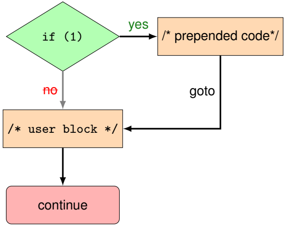

Compiletime-Codegeneration

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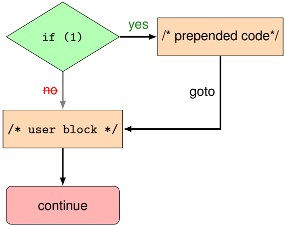
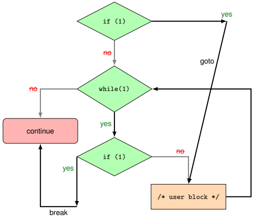


Append code to usercode

```
if (1)
  goto body;
else
  while (1)
    if (1) {
      /* appended code */
      break;
    }
    else body:
    {/* block following the macro */}
```



Compiletime-Codegeneration

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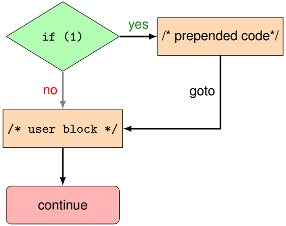

Append code to usercode

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if (1)
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  while (1)
    if (1) {
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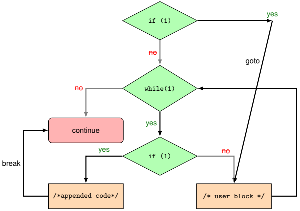

Compiletime-Codegeneration

All in one

```
if (1) {
  /* prepended code */
  goto body;
} else
   while (1)
     if (1) {
       /* appended code */
       break;
     }
     else body:
     { /* block following the expanded macro */ }
```

Compiletime-Codegeneration

```
#define concat_( a, b) a##b
#define label(prefix, lnum) concat_(prefix,lnum)
#define ATOMIC (lock)          \
if (1) {                       \
  acquire(&lock);              \
  goto label(body,__LINE__);   \
} else                         \
   while (1)                   \
     if (1) {                  \
       release(&lock);         \
       break;                  \
     }                         \
     else                      \
       label(body,__LINE__):
```

⚠ Reusability

labels have to be created dynamically in order for the macro to be reusable (→ `__LINE__`)

Homoiconic Metaprogramming

Homoiconic Programming

Homoiconicity

In a homoiconic language, the primary representation of programs is also a data structure in a primitive type of the language itself.

data is code
code is data

- Metaclasses and Metaobject Protocol
- (Hygienic) Macros

Reflection

Reflective Metaprogramming

Type introspection

A language with Type introspection enables to examine the type of an object at runtime.

Example: Java `instanceof`

```java
public boolean equals(Object o){
  if (!(o instanceof Natural)) return false;
  return ((Natural)o).value == this.value;
}
```

Reflective Metaprogramming

Metaclasses (→ **code is data**)

Example: Java Reflection / Metaclass `java.lang.Class`

```
static void fun(String param){
  Object incognito = Class.forName(param).newInstance();
  Class meta = incognito.getClass(); // obtain Metaobject
  Field[] fields = meta.getDeclaredFields();
  for(Field f : fields){
    Class t = f.getType();
    Object v = f.get(o);
    if(t == boolean.class && Boolean.FALSE.equals(v))
    // found default value
    else if(t.isPrimitive() && ((Number) v).doubleValue() == 0)
    // found default value
    else if(!t.isPrimitive() && v == null)
    // found default value
} }
```

Metaobject Protocol

Metaobject Protocol

Metaobject Protocol (MOP [1])

Example: Lisp’s CLOS metaobject protocol

... offers an interface to manipulate the underlying implementation of CLOS to adapt the system to the programmer’s liking in aspects of

- creation of classes and objects
- creation of new properties and methods
- causing inheritance relations between classes
- creation generic method definitions
- creation of method implementations
- creation of specializers (→ overwriting, multimethods)
- configuration of standard method combination (→ before,after,around, call-next-method)
- simple or custom method combinators (→ +,append,max,. . .)
- addition of documentation

Hygienic Macros

Homoiconic Runtime-Metaprogramming

Clojure! [2]

Clojure programs are represented after parsing in form of symbolic expressions (S-Expressions), consisting of nested trees:

S-Expressions

S-Expressions are either

- an atom
- an expression of the form $(x.y)$ with x, y being S-Expressions

Remark: Established shortcut notation for lists:

$$(x_1\ x_2\ x_3) \quad \equiv \quad (x_1\ .\ (x_2\ .\ (x_3\ .\ ())))$$

Homoiconic Runtime-Metaprogramming

Special Forms

Special forms differ in the way that they are interpreted by the clojure runtime from the standard evaluation rules.

Language Implementation Idea: reduce every expression to special forms:

```
(def symbol doc? init?)
(do expr*)
(if test then else?)
(let [binding*] expr*)
(eval form)  ; evaluates the datastructure form
(quote form) ; yields the unevaluated form
(var symbol)
(fn name? ([params*] expr*)+)
(loop [binding*] expr*)
(recur expr*) ; rebinds and jumps to loop or fn
;...
```

Homoiconic Runtime-Metaprogramming

Macros

Macros are configurable syntax/parse tree transformations.

Language Implementation Idea: define advanced language features in macros, based very few special forms or other macros.

Example: While loop:

```
(macroexpand '(while a b))
; => (loop* [] (clojure.core/when a b (recur)))

(macroexpand '(when a b))
;=> (if a (do b))
```

Homoiconic Runtime-Metaprogramming

Macros can be written by the programmer in form of S-Expressions:

```
(defmacro infix
  "converting infix to prefix"
  [infixed]
  (list (second infixed) (first infixed) (last infixed)))
```

...producing

```
(infix (1 + 1))
; => 2
(macroexpand '(infix (a + b)))
; => (+ a b)
```

⚠ Quoting

Macros and functions are directly interpreted, if not quoted via

```
(quote keyword)   ; or equivalently:
'keyword
; => keyword
```

Homoiconic Runtime-Metaprogramming

```
(defmacro fac1 [n]
   (if (= n 0)
     1
     (list '* n (list 'fac1 (- n 1))
 ))))
```

```
(defn fac2 [n]
   (if (= n 0)
     1
     (* n (fac2 (- n 1))
 ))))
```

```
(fac1 4)
; => 24
```

```
(fac2 4)
; => 24
```

...produces

```
(macroexpand '(fac1 4))
; => (* 4 (fac1 3))

(macroexpand-all '(fac1 4))
; => (* 4 (* 3 (* 2 (* 1 1))))
```

⇝ why bother?

Homoiconic Runtime-Metaprogramming

⚠ Macros vs. Functions

- Macros as static AST Transformations, vs. Functions as runtime control flow manipulations
- Macros replicate parameter forms, vs. Functions evaluate parameters once

⇝ Macro parameters are uninterpreted, not necessarily valid expressions, vs. Functions parameters need to be valid expressions

Homoiconic Runtime-Metaprogramming

⚠ Macro Hygiene

Shadowing of variables may be an issue in macros, and can be avoided by generated symbols!

```
(def variable 42)
(macro mac [&stufftodo] `(let [variable 4711] ~@stufftodo))
(mac (println variable))
; => can't let qualified name: variable
```

```
(macro mac [&stufftodo] `(let [variable# 4711] ~@stufftodo))
```

⇝ Symbol generation to avoid namespace collisions!

Further reading...

[1] R. P. Gabriel.
Gregor kiczales, jim des rivières, and daniel g. bobrow, the art of the metaobject protocol.
Artif. Intell., 61(2):331–342, 1993.

[2] D. Higginbotham.
Clojure for the Brave and True: Learn the Ultimate Language and Become a Better Programmer.
No Starch Press, San Francisco, CA, USA, 1st edition, 2015.

[3] S. Tatham.
Metaprogramming custom control structures in C.
`https://www.chiark.greenend.org.uk/~sgtatham/mp/`, 2012.
[Online; accessed 07-Feb-2018].