Compiling Haskell to LLVM

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Overview

Typical compiler pipeline

1. Parse language to an abstract syntax tree (AST)
2. Transform the AST (optimization, simplification, etc.)
3. Generate executable

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In this talk, we focus on the backend of the compiler.

Possible targets for generating executables

- Native assembly
  - Very fast

x86 assembly

```
f:
pushl   %ebp
movl    %esp, %ebp
subl    $8, %esp
movl    12(%ebp), %eax
movl    %eax, (%esp)
call    g
imull   8(%ebp), %eax
leave
ret
```

Possible targets for generating executables

- Native assembly
    - Very fast
- High level languages (C, Java, etc.)
    - Portable
    - Fast

C

```
int f( int x, int y )
{
  return x * g( y );
}
```

Possible targets for generating executables

- Native assembly
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- High level languages (C, Java, etc.)
  - Portable
  - Fast
- Managed virtual environments (JVM, CLI, etc)
  - Portable
  - Rich environment

Java byte code

```
static int f(int, int);
  Code:
   0:iload_0
   1:iload_1
   2:invokestatic #2; //g
   5:imul
   6:ireturn
```

Possible targets for generating executables

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- Managed virtual environments (JVM, CLI, etc)
  - Portable
  - Rich environment
- Typed assembly languages
  - What are they?

LLVM assembly

```
define i32 @f( i32 %x
             , i32 %y )
{
  %vr.0 = call i32
          @g( i32 %y )
  %vr.1 = mul i32 %x, %vr.0
  ret i32 %vr.1
}
```

Typed assembly languages

Definition

- Architecture neutral
- Statically typed
- Optionally high level features

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A universal intermediate representation that high level languages can be mapped to.

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A universal intermediate representation that high level languages can be mapped to.

Advantages:

- Portable
- Very fast
- Very flexible

Possible targets for Haskell compilers

- Native assembly:
  - Hard to maintain
- C:
  - No efficient tail call support
- Managed virtual environments:
  - Run-time system optimized for imperative languages

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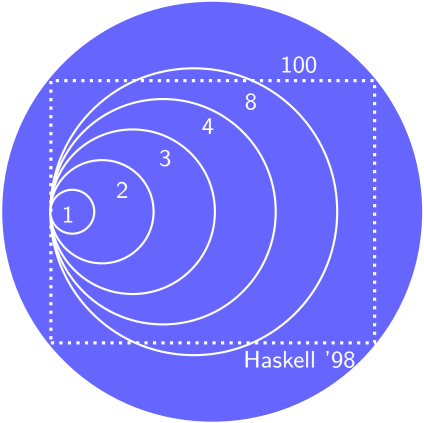
Are typed assembly languages suitable targets for Haskell compilers?

EHC

The Essential Haskell Compiler (EHC).

- Actively developed at Utrecht University by Atze Dijkstra and Jeroen Fokker
- Executable generation via C
- Allows for easy experimentation with 'variants'

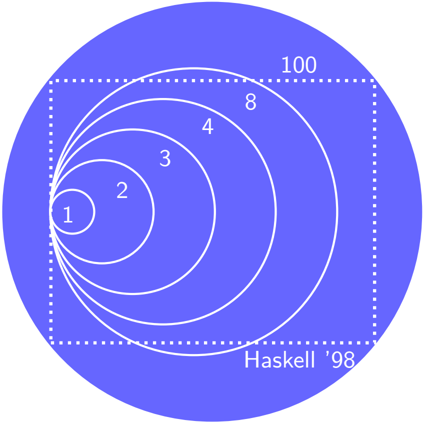
EHC variants



EHC is a sequence of compilers

- Variant 1: Explicitly typed lambda calculus
- Variant 8: Code generation
- Variant 100: Full Haskell 98, some extensions

EHC variants



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- Variant 1: Explicitly typed lambda calculus
- Variant 8: Code generation
- Variant 100: Full Haskell 98, some extensions

We will use variant 8 for all examples in this talk.

LLVM

The Low Level Virtual Machine (LLVM) compiler infrastructure project.

- Actively developed at Apple, main developer Chris Lattner
- Mature optimizing compiler framework
- Supports 11 different architectures, including x86, PowerPC, Alpha, and SPARC

The LLVM assembly language

- Infinite amount of virtual registers
- RISC format
- Stack management
- Strongly typed
- Static single assignment (SSA)

The LLVM assembly language - Example

LLVM assembly example - increment counter

```
@globalCounter = global i32 0

define fastcc void @incrGlobalCounter( i32 %by )
{
  %vr0 = load i32* @globalCounter
  %vr1 = add i32 %vr0 , %by
   store i32 %vr1 , i32* @globalCounter
   ret void
}
```

The LLVM assembly language - Example

%vr*n* are virtual registers

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The LLVM assembly language - Example

%vr*n* are virtual registers

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High level function calls

All operations are typed.

Each virtual register assigned once.

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Research questions

Question: Is the LLVM assembly language a suitable target for EHC?

1. *a)*: Is the implementation as easy as targeting C?
2. *b)*: Is the generated code efficient?

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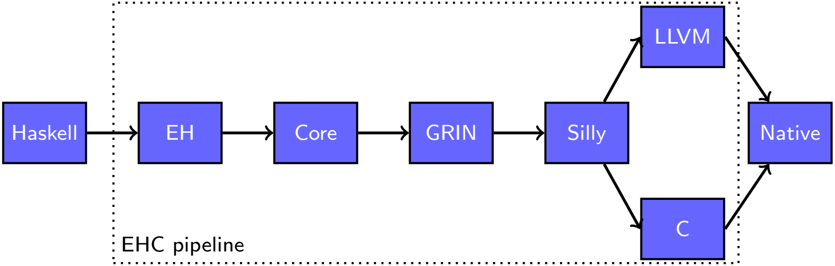
2. *b)*: Is the generated code efficient?

Contributions

- An implementation of a EHC backend that creates executables via LLVM assembly.
- A comparison of execution time and memory usage between the LLVM and C targeting backends.
- Suggestions for more efficient code generation by EHC and the impact of these changes.

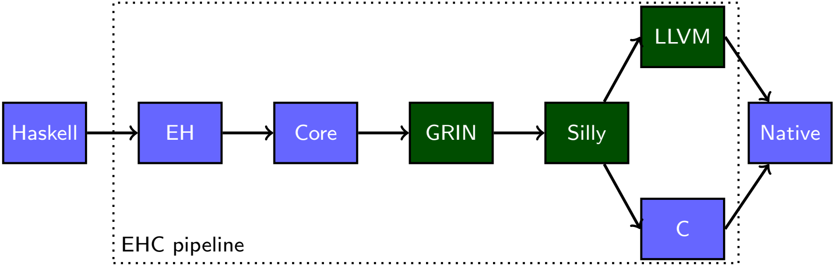
Implementation

Pipeline stages



- *Essential Haskell (EH)*: desugared Haskell
- *Core*: lambda calculus with some extensions
- *GRIN*: makes evaluation order of the program explicit
- *Silly*: foundation for translation to imperative languages

Pipeline stages



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Running example

Running example

```haskell
fib :: Int -> Int
fib n    | n == 0   = 0
         | n == 1   = 1
         | True     = fib (n-1) + fib (n-2)

main = fib 33
```

GRIN - Overview

The Graph Reduction Intermediate Notation (GRIN)

- Developed by Urban Boquist
- Makes expression evaluation order explicit
- A very efficient evaluation model
- Closed world assumption

GRIN - Representation of expressions

- Expressions represented as nodes.

Definition of nodes

A node is a sequence of fields, where the first field is a tag, followed by zero or more payload fields.

- 3 type of nodes:
  - Constructed values (C)
  - Suspended functions (F)
  - Partial applications (P)

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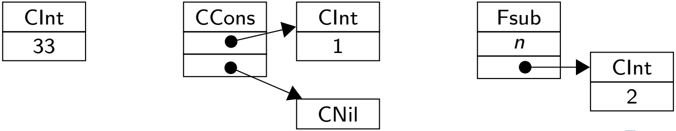

GRIN - Haskell to GRIN

- Erase type information
- Transform to SSA form
- Explicit access to memory
- Add evaluation order to program
  - Expressions translated to a graph
  - Graph evaluated to WHNF

GRIN - Generated code

Recursive case of fib

```
$fib $p1 =
  [...]
  store (CInt 2); λ$p2 →
  store (Fsub $p1 $p2); λ$p3 →
  store (Ffib $p3); λ$p4 →
  store (CInt 1); λ$p5 →
  store (Fsub $p1 $p5); λ$p6 →
  store (Ffib $p6); λ$p7 →
  store (Fadd $p7 $p4); λ$p8 →
  $eval $p8
```

GRIN - Generated code

Each variable is assigned exactly once.

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Only *store*, *update*, and *load* perform memory access.

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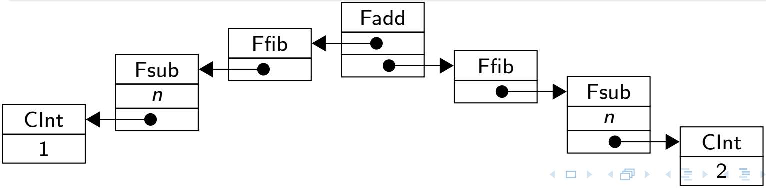

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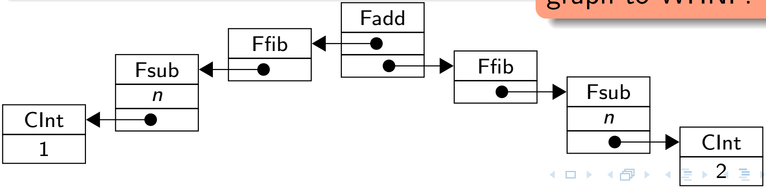
eval evaluates the graph to WHNF.



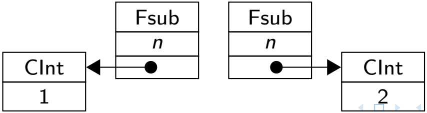
Silly - GRIN to Silly

- Abstracts over the transformations of GRIN to an imperative language
- Language has an imperative feel
- Consists of only well supported constructs (assignment, switch, function call, variable, constant etc.)
- Decides on physical representation of nodes
  - A node is an array of *heap cells*
- Introduces local and global variables
  - Global variables: return node and constant applicable form nodes
  - Local variables: value depends on control flow

Silly - Generated code

Recursive case of fib

```
p3     := allocate(3) { GCManaged };
p3[0]  := Fsub;
p3[1]  := p1;
p3[2]  := global_p2;
p6     := allocate(3) { GCManaged };
p6[0]  := Fsub;
p6[1]  := p1;
p6[2]  := global_p5;
fun_fib(p6);
i72    := RP[1];
fun_fib(p3);
i92    := foreign primAddInt(i72, RP[1]);
```



Silly - Generated code

Array indexes used to access fields of nodes

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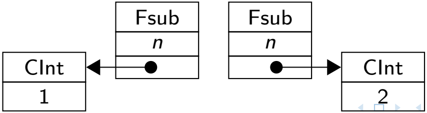

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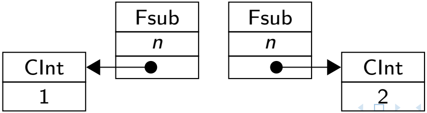

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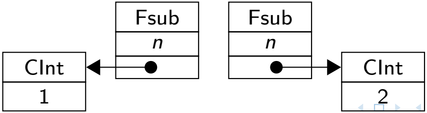
Prefix *global_* for global variables.



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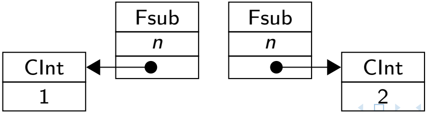
RP is the global return array.



Generating LLVM assembly

LLVM - Silly to LLVM

- Infer LLVM types
- Generate LLVM instructions
- Extract C strings

LLVM - Inferring LLVM types

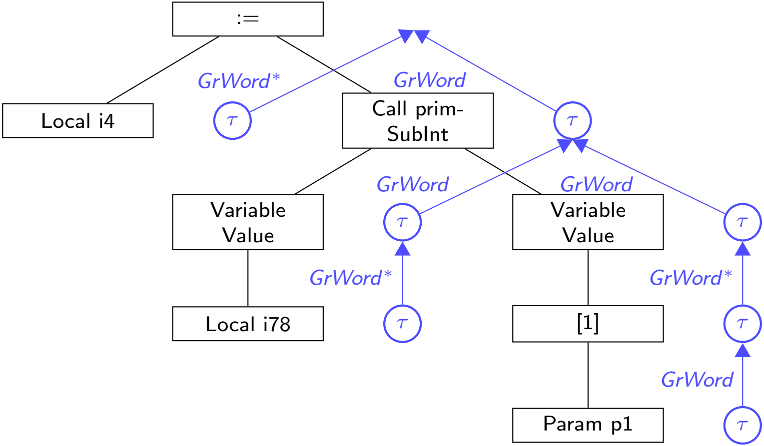
- Types are erased in early stages of the pipeline
- To allow re-typing, we use the following trick:
  - Define *GrWord* as an integer with the same size as a native pointer
  - This allows us to store integers and pointers at the same location
  - Example: CCons node
- Each Silly statement is typed in isolation.
- Instruction generation uses type information to insert type conversions.

LLVM - Inferring LLVM types (2)

- We have the following assumptions:
    - Global variables: *GrWord***
    - Local variables: *GrWord**
    - Parameter variables: *GrWord*
    - Allocations: *GrWord*
    - Constants: *GrWord*
- Each leaf in a Silly AST matches one of these cases.
- Other nodes use types of children and local information.
- Easy to implement with an attribute grammar.

LLVM - Inferring LLVM types (3)

Type inference of *i4 := foreign primSubInt(i78, p1[1]);*



LLVM - Generate instructions

- Instruction generation is a 3 step process:
  - Acquire result variables from child AST nodes.
  - Generate code to convert the types of result variables to the expected types.
  - Generate code for the semantics of this node.

LLVM - Generate instructions (2)

i4 := foreign primSubInt(i78, p1[1]);

```
; Convert p1 to GrWord*
%vr0 = inttoptr i32 %p1 to i32*

; Get pointer to field 1 of p1
%vr1 = getelementptr i32* %vr0, i32 1

; Load pointer to field 1 of p1
%vr2 = load i32* %vr1

; Load local variable i78 from memory
%vr3 = load i32* %i78

; Do function call
%vr4 = call i32 @primSubInt( i32 %vr3, i32 %vr2 )

; Store result in i4
store i32 %vr4, i32* %i4
```

LLVM - Extracting C Strings

- Strings not part of executable code.
- Inline strings collected and defined constant.
- Implemented with 1 AG threaded attribute.

LLVM - Implementation compared to C

- Although LLVM is more low level, the backend implementation does not differ much:
  - GRIN prepares for SSA form.
  - Silly abstracts over imperative backends.
  - All Silly constructs easily mappable to LLVM.
  - Attribute grammars help keep implementation of bottom-up algorithms concise.

Results

Results - Benchmark situation

Comparing the C and LLVM backend by compiling 8 nofib programs.

We measure the pure gain of targeting LLVM instead of C[a].

- Both compiled with full optimization.
- Both use the same run time system.
- Both allocate with `malloc()` and do not de-allocate.
- Machine had enough memory to avoid swapping.

[a] compiled with GCC

Results - The numbers

program	time (Δ%)	memory allocated (Δ%)
digits-of-e1	24.1%	
digits-of-e2	8.1%	
exp3_8	-9.4%	
primes	8.8%	
queens	17.7%	
tak	23.6%	
wheel-sieve1	22.1%	
wheel-sieve2	10.2%	
average	13.1%	

Positive Δ: LLVM backend performs better than the C backend.

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Results - The numbers explained

Why is the LLVM compiler more efficient?

- C backend uses shadow stack for tail calls
- C used as portable assembly
- Aliasing problem

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Why is the LLVM compiler more efficient?

- C backend uses shadow stack for tail calls
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Slowdown of the program exp3_8:

- Native backend of the C compiler does a better job.
- This is work in progress for LLVM.

Conclusion

Future work

- Simplify the implementation of the backend.
  - Perform typing in Silly
  - (alternative) Propagate types to the back end.

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  - Return result of functions in registers instead of a global variable
  - Allocate global variables statically
  - More efficient memory management

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  - (alternative) Propagate types to the back end.
- Increase performance of the generated code:
  - Return result of functions in registers instead of a global variable
  - Allocate global variables statically
  - More efficient memory management
- Validate suitability of LLVM as backend target with other Haskell compilers

Conclusion

For EHC, LLVM is a more favourable target than C.

- Complexity comparable to generation of C
- Run time reduced with 13.1% by average

There is still much room for improvement, not a production compiler yet.