Lecture 12: Nanopass Compilation

Talen en Compilers 2024-2025, period 2

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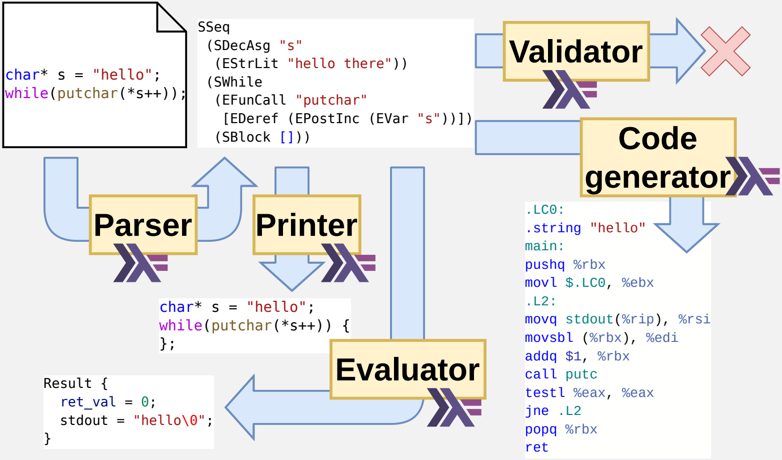
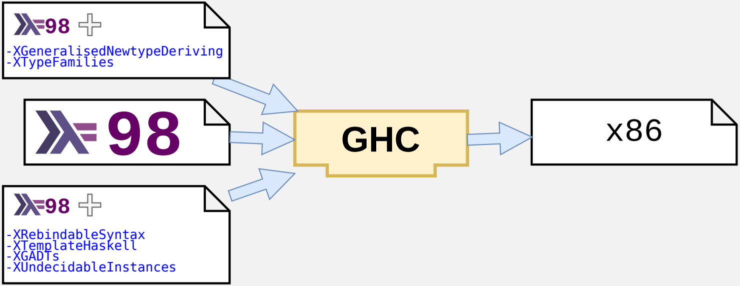
Compiler Architecture



Compiler Architecture affects scalability

Compiler Architecture affects scalability



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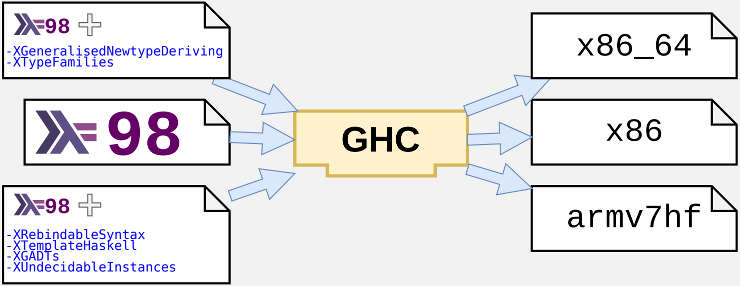
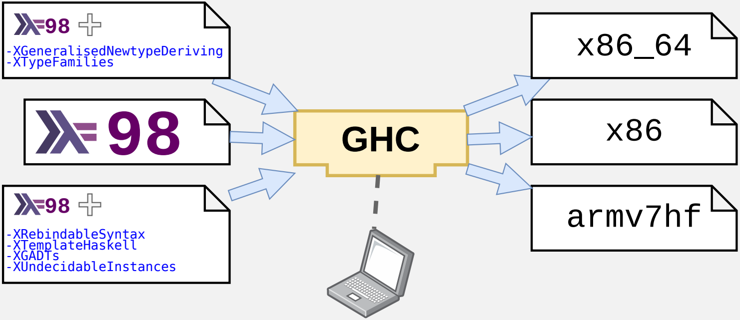
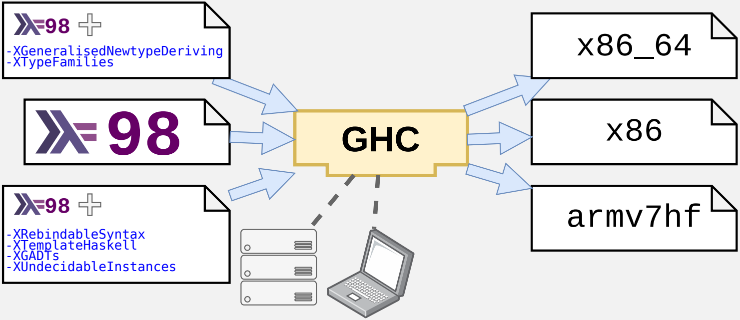
Compiler Architecture affects scalability



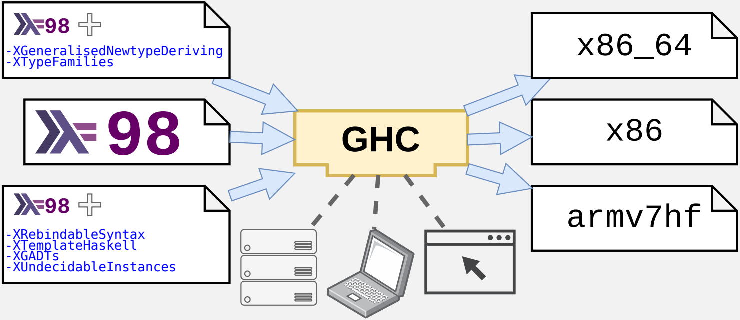
Compiler Architecture affects scalability



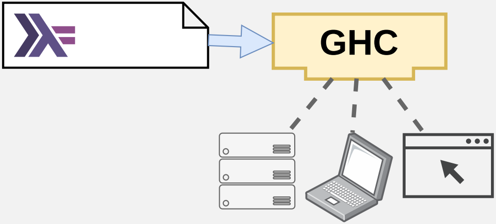
Compiler Architecture affects scalability



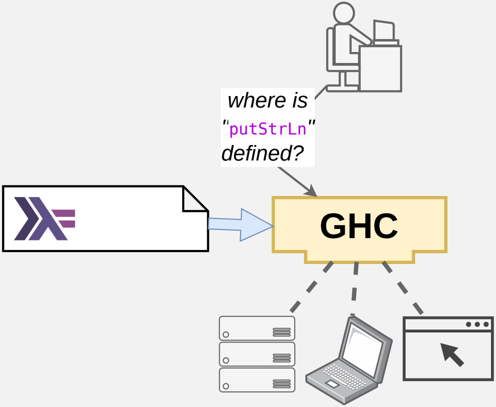
Compiler Architecture affects scalability



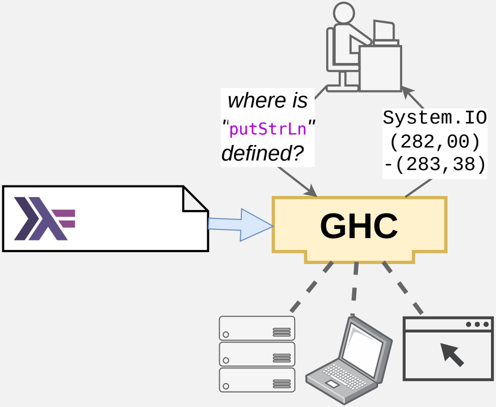
Compiler Architecture affects scalability



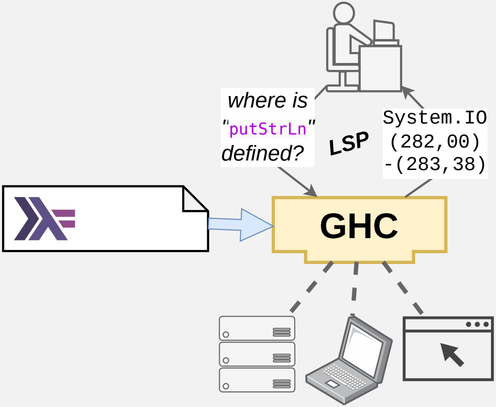
Compiler Architecture affects scalability



Compiler Architecture affects scalability



Compiler Architecture affects scalability



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Compiler Architecture is hard

17 **r/haskell** • u/heisenbug • Dec 30 '11

Current state of GHC cross compilers?

There might be a slight chance to introduce Haskell into a small, well defined embedded environment, but our tools are x86-64 Linux based, and we would need a cross GHC targetting PowerPC32. What is the state of cross compilation in v7.4.1? Are the TODOs marked in the wiki page done? Any magic arm twisters needed? (Which would be okay, as I am open for experiments.)

permalink reddit 88% Upvoted

6 comments sorted by Confidence → Search comments

3 ▾ u/barsoap Dec 31 '11

Not good. But that is, as the wiki page you're linking, about cross-compiling ghc, which is more complex than cross-compiling any random app, primarily because your app's build system isn't as scary as GHC's. The main issue is that the build system just doesn't properly distinguish between target and donour, neither in terms of system headers or .o files, resulting in fun bugs like code thinking directories are files.

You're probably going to have to build the rts for your target platform basically by hand, as the base libraries... but you can ignore base on the first try and just do a ffi call to your platform's puts or something.

Prepare to learn a lot of make if you aren't a wizard, yet. The build system isn't for the faint of heart.

2 ▾ u/heisenbug Jan 01 '12

Compiler Architecture is hard

17 **r/haskell**

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2 ▾

23 **r/Zig** • u/[deleted] • Mar 26 '20

What is so great/hard about cross compilation?

I read Andrew's newest article (https://andrewkelley.me/post/zig-cc-powerful-drop-in-replacement-gcc-clang.html) last night and after reading through the comments on various sites it seems that people are pretty impressed by the cross compilation feature.

I don't have a CS background so I am just lacking the knowledge to appreciate this, but why is cross compilation so great/hard?

Here's my current understanding, feel free to correct any assumptions that are incorrect:

A compiler is a program that translates source code into machine code. I compile something and I get a working binary. That binary works, because the compiler understands how to transform source code into machine code. Every single time. So the "formula" is known and understood.

Let's say I code an image library. It takes an SVG file and converts it to a JPEG. This works every time I run it. Flawlessly. This works because my program understands both the SVG format as well as the JPEG format. Now let's further assume I add the possibility to also convert SVG files to PNG. This works because my program now understands the SVG format, the JPEG format and now also the PNG format. But nobody would say "oh my god this is so great I can now do PNG as well". However this seems to be the case with cross compilation.

Why is it not mind-blowing if my image library can convert a SVG image to both JPEG and PNG?

Why is it mind-blowing that the zig compiler can convert source code to both Linux and macOS (and other) binaries?

We have had C compilers for decades on many different platforms. So we know the formula for how to convert source code to many different machine codes. If we know that formula just like we know it for SVG-to-JPEG and SVG-to-PNG conversion then why is it so special?

I hope you can understand where my confusion lies. I'd really like to understand this, but it hasn't quite made "click" yet.

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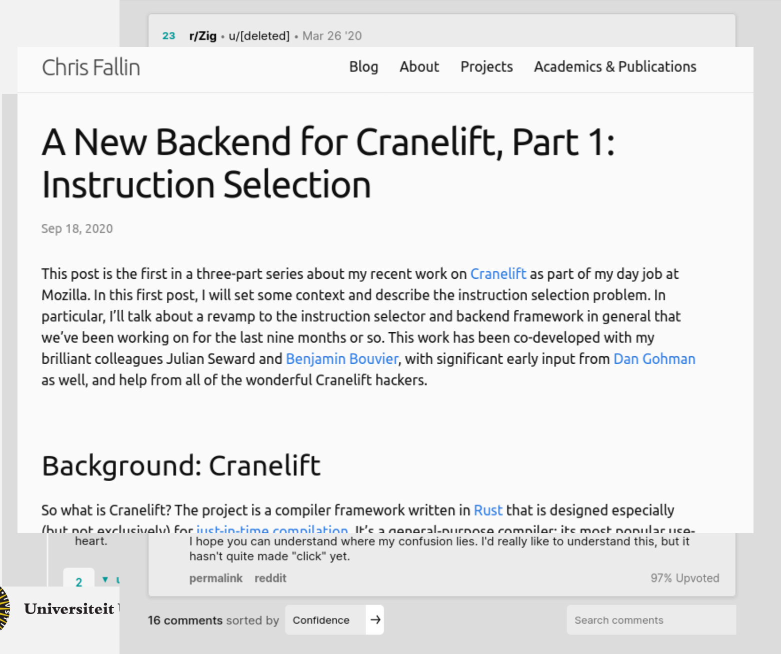
Compiler Architecture is hard



23 r/Zig • u/[deleted] • Mar 26 '20

Chris Fallin Blog About Projects Academics & Publications

A New Backend for Cranelift, Part 1: Instruction Selection

Sep 18, 2020

This post is the first in a three-part series about my recent work on Cranelift as part of my day job at Mozilla. In this first post, I will set some context and describe the instruction selection problem. In particular, I'll talk about a revamp to the instruction selector and backend framework in general that we've been working on for the last nine months or so. This work has been co-developed with my brilliant colleagues Julian Seward and Benjamin Bouvier, with significant early input from Dan Gohman as well, and help from all of the wonderful Cranelift hackers.

Background: Cranelift

So what is Cranelift? The project is a compiler framework written in Rust that is designed especially

heart.

I hope you can understand where my confusion lies. I'd really like to understand this, but it hasn't quite made "click" yet.

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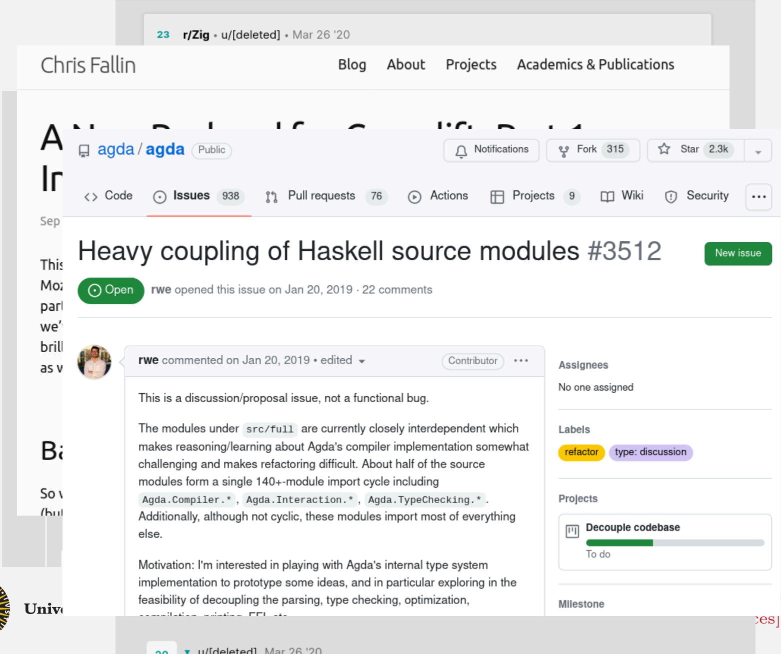
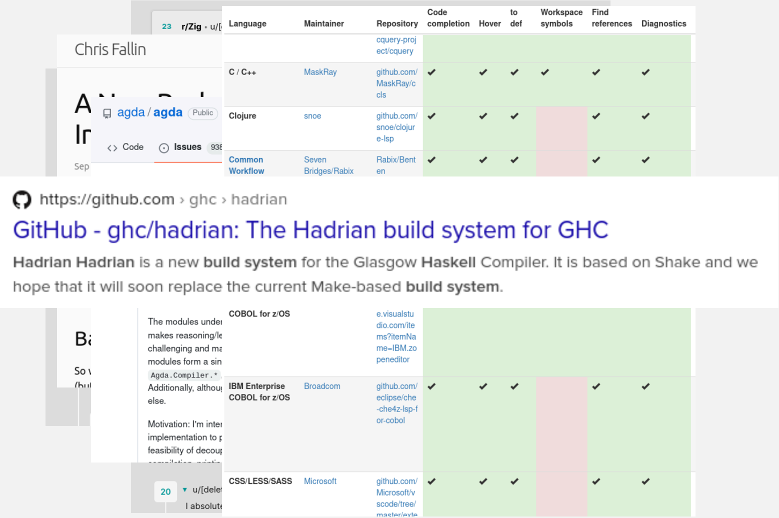
Compiler Architecture is hard



Compiler Architecture is hard

Language	Maintainer	Repository	Code completion	Hover	to def	Workspace symbols	Find references	Diagnostics
		cquery-project/cquery						
C / C++	MaskRay	github.com/MaskRay/ccls	✔	✔	✔	✔	✔	✔
Clojure	snoe	github.com/snoe/clojure-lsp	✔	✔	✔		✔	✔
Common Workflow Language (CWL)	Seven Bridges/Rabix	Rabix/Benten	✔	✔	✔		✔	✔
Coq	Coq LSP Team	coq-lsp		✔				✔
Cucumber (Gherkin)	Cucumber core team	cucumber/language-server	✔					✔
IBM Enterprise COBOL for z/OS	IBM	marketplace.visualstudio.com/items?itemName=IBM.zopeneditor	✔	✔	✔	✔	✔	✔
IBM Enterprise COBOL for z/OS	Broadcom	github.com/eclipse/che-che4z-lsp-for-cobol	✔	✔	✔		✔	✔
CSS/LESS/SASS	Microsoft	github.com/Microsoft/vscode/tree/master/exte	✔	✔	✔		✔	✔

Compiler Architecture is hard



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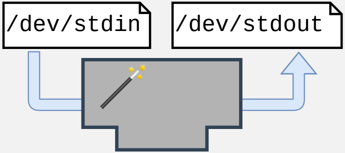
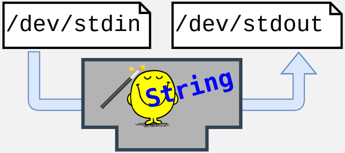
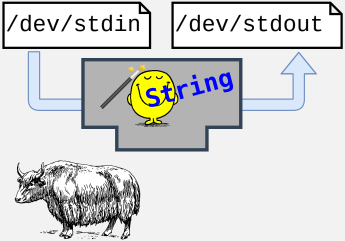
Compiler Architecture: monolith



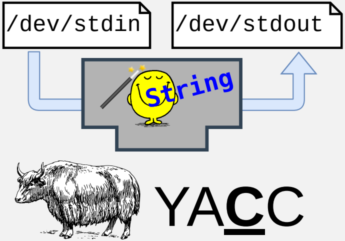
Compiler Architecture: monolith



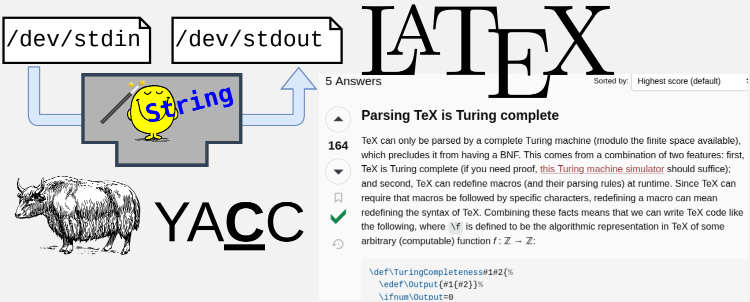
Compiler Architecture: monolith



Compiler Architecture: monolith



Compiler Architecture: monolith



5 Answers

Sorted by: Highest score (default)

164

Parsing TeX is Turing complete

TeX can only be parsed by a complete Turing machine (modulo the finite space available), which precludes it from having a BNF. This comes from a combination of two features: first, TeX is Turing complete (if you need proof, this Turing machine simulator should suffice); and second, TeX can redefine macros (and their parsing rules) at runtime. Since TeX can require that macros be followed by specific characters, redefining a macro can mean redefining the syntax of TeX. Combining these facts means that we can write TeX code like the following, where `\f` is defined to be the algorithmic representation in TeX of some arbitrary (computable) function $f : \mathbb{Z} \to \mathbb{Z}$:

```
\def\TuringCompleteness#1#2{%
  \edef\Output{#1{#2}}%
  \ifnum\Output=0
```

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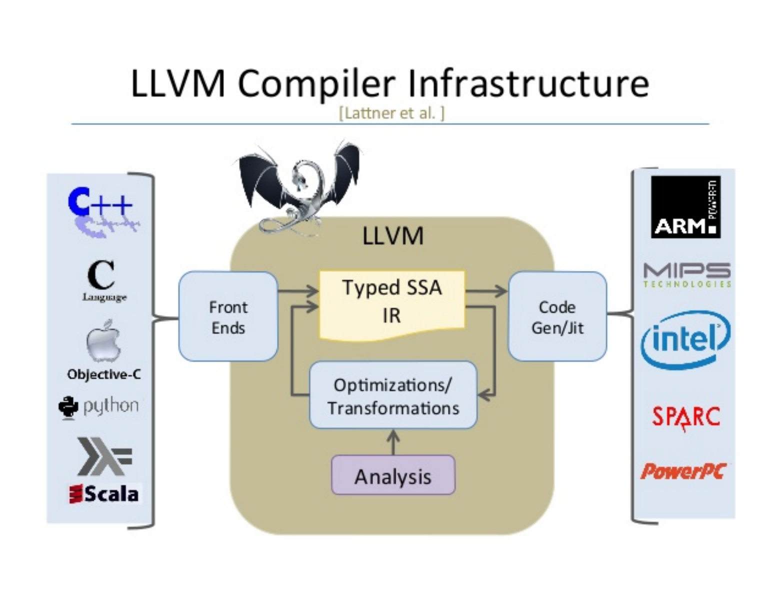
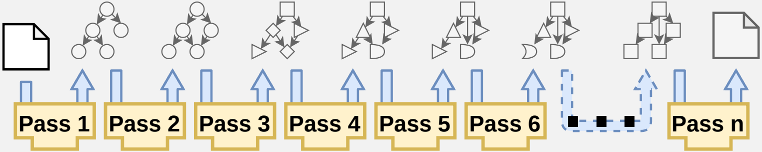
Compiler Architecture: multi-pass



By P. Teoh on SO, https://stackoverflow.com/a/49081640

Compiler Architecture: nanopass



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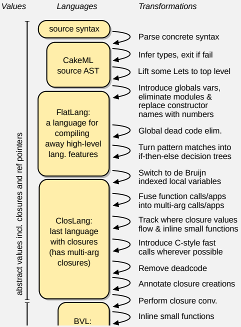
Compiler Architecture: nanopass

https://cakeml.org/

Compiler Architecture: nanopass

CAKEML
A Verified Implementation of ML

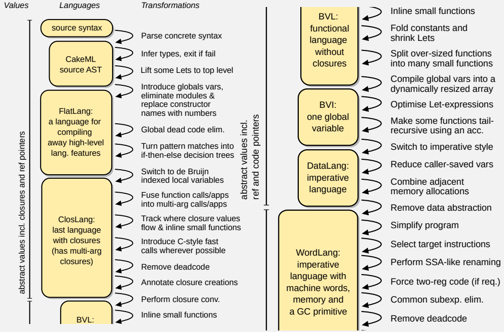
https://cakeml.org/



Compiler Architecture: nanopass

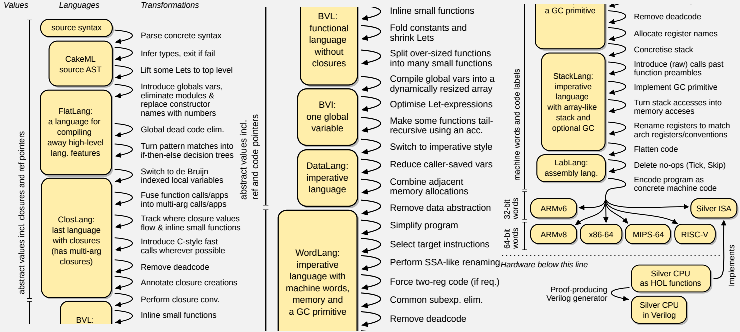
CAKEML
A Verified Implementation of ML

https://cakeml.org/



Compiler Architecture: nanopass

https://cakeml.org/



Nanopass: Parse

```
char* s = "hello";
while (
  putchar(*s++)
 );
```

```
char* s = "hello";
while (
  putchar(*s++)
 );
```

Nanopass: Type-Check

```
real_solns :: _ -> _ -> _
real_solns a b c =
  let d = b**2 - 4*a*c in
  if d >= 0 then
    [(-b + sqrt d) / (2*a)
    ,(-b - sqrt d) / (2*a) ]
  else []
```

```
real_solns :: Float -> Float -
real_solns a b c =
  let d = b**2 - 4*a*c :: Floa
  if d >= (0 :: Float) then
    [(-b + sqrt d) / (2*a)
    ,(-b - sqrt d) / (2*a) ]
  else []
```

Nanopass: `for` → `while`

```
for(int i = 0;
    i < l.length;
    i++) {
  do_stuff();
}
```

```
int i = 0;
while(i < l.length) {
  do_stuff();
  i++;
}
```

Nanopass: for → while

```
for(int i = 0;
    i < l.length;
    i++) {
  do_stuff();
}
```

```
int i = 0;
while(i < l.length) {
  do_stuff();
  i++;
}
```

```
for2while :: AstF → AstW
for2while (For (i,c,n) b) =
    i `Seq` While c (b `Seq` n)
for2while (Call f)    = Call f
for2while (Var i)     = Var i
for2while (Add e1 e2) = Add e1 e2
for2while (Seq e2 e2) = Seq e2 e2
for2while ...
```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Nanopass: for → while

```
for(int i = 0;
    i < l.length;
    i++) {
  do_stuff();
}
```

```
int i = 0;
while(i < l.length) {
  do_stuff();
  i++;
}
```

```
for2while' = AstFAlg {
  for = λ (i,c,n) b →
    i `Seq` While c (e `Seq` n);
  var = λ i       → Var i;
  add = λ e1 e2 → Add e1 e2;
  seq = λ e1 e2 → Seq e1 e2;
  ...}
```

Nanopass: for → while

```
for(int i = 0;
    i < l.length;
    i++) {
  do_stuff();
}
```

```
int i = 0;
while(i < l.length) {
  do_stuff();
  i++;
}
```

```
for2while' = AstFAlg {
  for = λ (i,c,n) b →
    i `Seq` While c (e `Seq` n);
  var = Var; add = Add; seq = Seq;
  ...}
```


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Nanopass: $\lambda \rightarrow$ class

```
int[] squares (int[] l) {

 return
  sum( map( (x => x*x)
          , l
    ));
}
```

```
int[] squares (int[] l) {

 return
  sum( map( new Lam43()
          , l
    ));
}

class Lam43 : Runnable {
 object run (object x) {
  return x*x;
 }

}
```

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Nanopass: $\lambda \rightarrow$ class

```
int[] squares (int[] l) {
 Logger q = get_logger();
 return
  sum( map( (x => q.log(x*x))
          , l
     ));
}
```

```
int[] squares (int[] l) {

 return
  sum( map( new Lam43()
          , l
     ));
}

class Lam43 : Runnable {
 object run (object x) {
  return x*x;
 }

}
```


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Nanopass: $\lambda \rightarrow$ class

```
int[] squares (int[] l) {
 Logger q = get_logger();
 return
  sum( map( (x => q.log(x*x))
          , l
    ));
}
```

```
int[] squares (int[] l) {
 Logger q = get_logger();
 return
  sum( map( new Lam43(q)
          , l
    ));
}

class Lam43 : Runnable {
 object run (object x) {
  return q.log(x*x);
 }
 Logger q;
}
```


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Nanopass: class → struct

```
class Player {
 uint coins;
 int hiscore;

 void again(){
  if(coins-- > 0) {
   int score = play();
   hiscore =
    max(score, hiscore);
  }
 }
}
```

```
struct Player {
 uint coins;
 int hiscore;
}
void again(Player* self){
 if(self->coins-- > 0){
  int score = play();
  self->hiscore =
    max(score, self->hiscore)
 }
}
```

Nanopass: Insert Reference-Counting code

```
void test() {
  int[] xs =
    list(1,1000000);
  int[] ys =
    map(xs, inc);

  print(ys);

}
```

```
void test() {
  int[] xs =
    list(1,1000000);
  int[] ys =
    map(xs, inc);
  _drop(xs);
  print(ys);
  _drop(ys);
}
```

Nanopass: Insert Reference-Counting code

```
void test() {
  int[] xs =
    list(1,1000000);
  int[] ys =
    map(xs, inc);

  print(ys);

}
```

```
void test() {
  int[] xs =
    list(1,1000000);
  int[] ys =
    map(xs, inc);
  _drop(xs);
  print(ys);
  _drop(ys);
}
```

https://www.microsoft.com/en-us/research/uploads/prod/2020/11/perceus-tr-v1.pdf

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){
  float pi = 3.13159;
  return 4 * pi * r * r;
}
```

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){

  return 4 * 3.13159 * r * r;
}
```

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){

  return 12.52636 * r * r;
}
```


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Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){

  return 12.52636 * r * r;
}
```

- Not essential

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){

  return 12.52636 * r * r;
}
```

- Not essential
- Might improve the code

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){

  return 12.52636 * r * r;
}
```

- Not essential
- Might improve the code
- “Optimisation”

Nanopass: Constant folding

```
float sphere_area(float r){
  float pi = calc_pi(5);
  return 4 * pi * r * r;
}
```

```
float sphere_area(float r){

  return 12.52636 * r * r;
}
```

- Not essential
- Might improve the code
- “Optimisation”
- More on Tuesday

Nanopass: `if`,`while`,... → `goto`

```
if {
  l.length > 7
}
then {
  u = insertion_sort(l)
}
else {
  u = quick_sort(l)
}
```

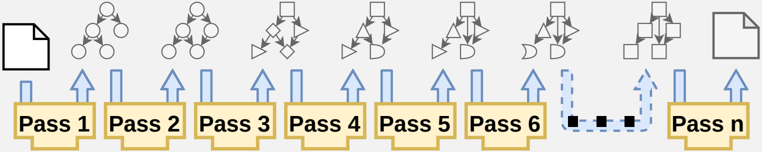
```
.L0:
  l.length > 7
  branch .L1 .L2
.L1:
  u = insertion_sort(l)
  goto .L3
.L2:
  u = quick_sort(l)
  goto .L3
.L3:
```

Nanopass: SSM instructions → x86_64 instructions

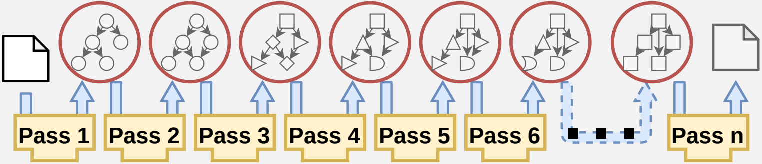
```
global.get   __stack_pointer
local.set    3
i32.const    32
local.set    4
local.get    3
local.get    4
i32.sub
local.set    5
local.get    5
global.set   __stack_pointer
i32.const    1
local.set    6
local.get    2
local.set    7
local.get    6
local.set    8
local.get    7
local.get    8
```

```
sub    rsp, 88
mov    qword ptr [rsp + 8], rd
mov    qword ptr [rsp + 16], r
mov    qword ptr [rsp + 24], r
mov    qword ptr [rsp + 32], r
cmp    rdx, 1
ja     .LBB0_2
mov    rax, qword ptr [rsp + 3
mov    rcx, qword ptr [rsp + 2
mov    rdx, qword ptr [rsp + 8
mov    rsi, qword ptr [rsp + 1
mov    qword ptr [rcx], rsi
mov    qword ptr [rcx + 8], rd
mov    rsi, qword ptr [rip + .
mov    rdx, qword ptr [rip + .
mov    qword ptr [rcx + 32], r
mov    qword ptr [rcx + 40], r
lea    rdx, [rip + .L.__unnamed
```

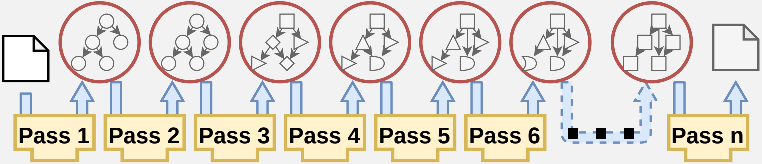
Nanopass AST(s)?



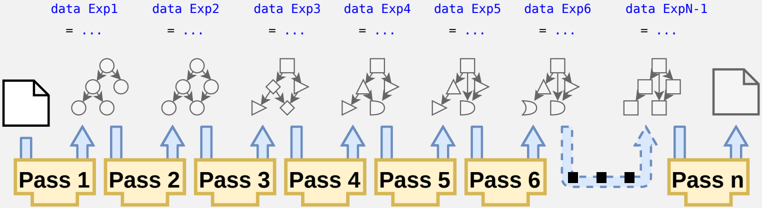
Nanopass AST(s)?



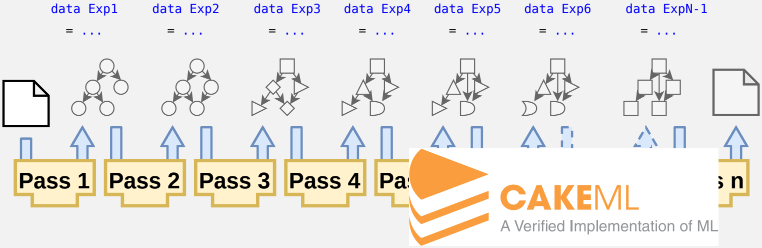
Design 1: Many ASTs



Design 1: Many ASTs



Design 1: Many ASTs



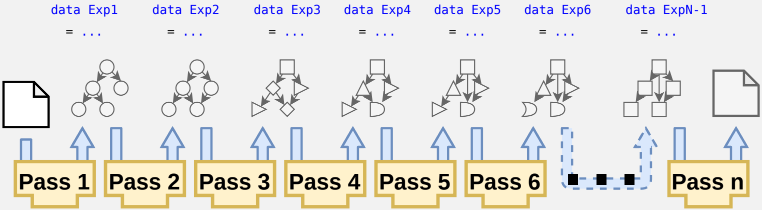
Design 1: Many ASTs ⇒ 💩 Repetition

```
data Exp3
  = For (Exp3,Exp3,Exp3) Exp3
  | While Exp3 Exp3
  | Call Func
  | Var Var
  | Add Exp3 Exp3
  | Seq Exp3 Exp3
  | ...
```

```
data Exp4

  = While Exp4 Exp4
  | Call Func
  | Var Var
  | Add Exp4 Exp4
  | Seq Exp4 Exp4
  | ...
```

Design 1: Many ASTs ⇒ 💩 Brittle pass order



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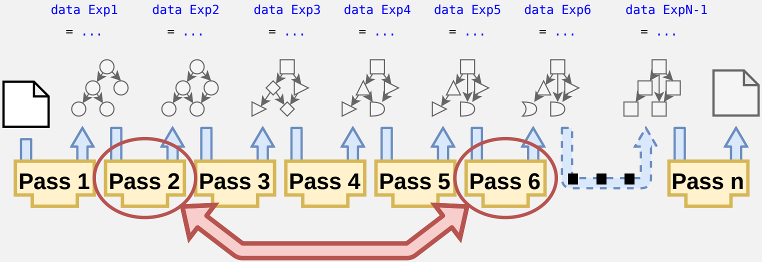
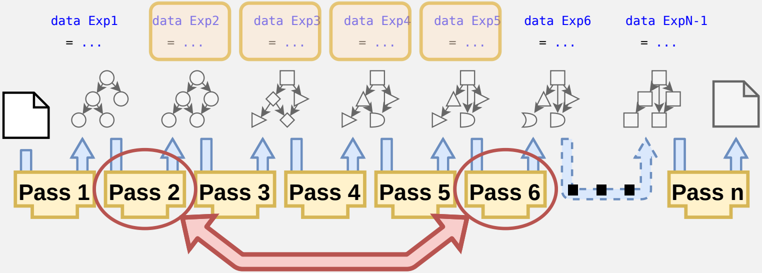
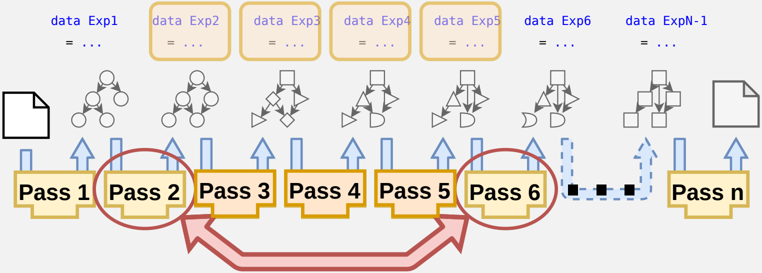
Design 1: Many ASTs ⇒ 💩 Brittle pass order



Design 1: Many ASTs ⇒ 💩 Brittle pass order



Design 1: Many ASTs ⇒ 💩 Brittle pass order



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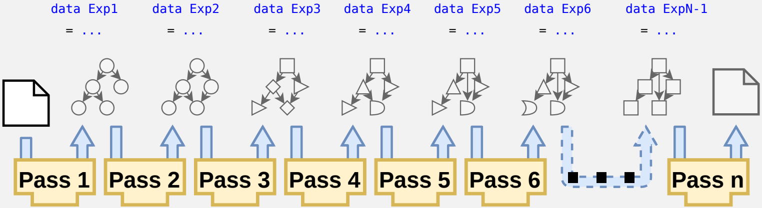
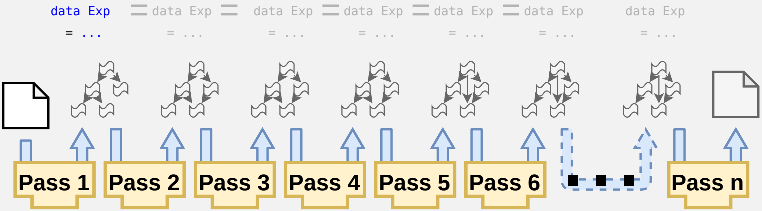
Design 2: One AST



Design 2: One AST



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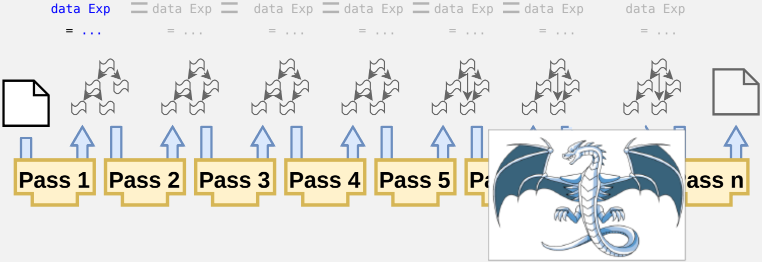
Design 2: One AST



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Design 2: One AST

```
data Exp
  = Raw String
  | If Exp Exp Exp
  | Goto Label
  | Instr SSM.Instr
  | Typed Type Exp
  | For (Exp,Exp,Exp) Exp
  | While Exp Exp
  | ...
```


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Design 2: One AST ⇒ 💩 No type safety

```haskell
for2while :: Exp → Exp
for2while (For (i,c,n) b) =
    i `Seq` While c (b `Seq` n)
for2while (Call f)      = Call f
for2while (Var i)       = Var i
for2while (Add e1 e2) = Add e1 e2
for2while (Seq e2 e2) = Seq e2 e2
for2while ...
```

```
<interactive>:10:18: warning: [-Wincomplete-patterns]
    Pattern match(es) are non-exhaustive
    In an equation for `for2while':
        Patterns of type `Exp' not matched:
          rawCode :: String -> Exp
          goto    :: Label -> Exp
          instr   :: SSM.Instr -> Exp
          ...
```

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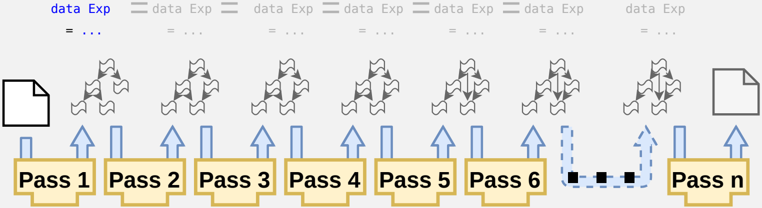
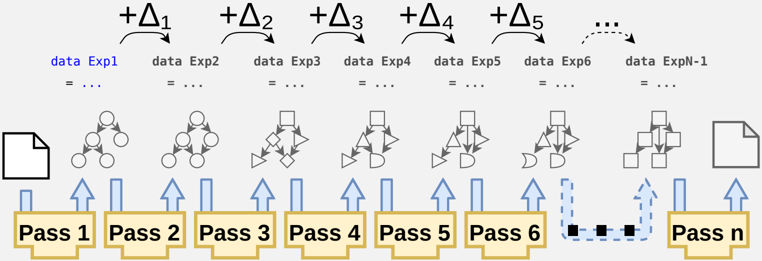
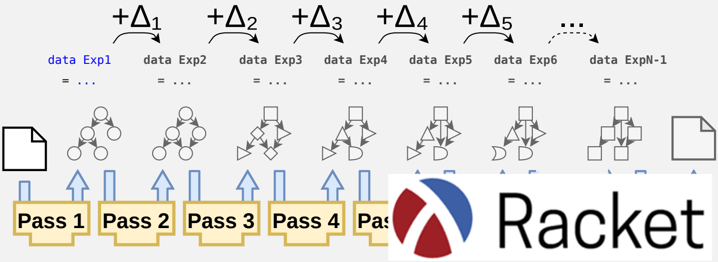
Design 3: Generics



Design 3: Generics



Design 3: Generics



Design 3: Generics ⇒ 💩 Not Haskell

```
{-# LANGUAGE TemplateHaskell #-}
import Vaporware.Generics.Library
```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Design 3: Generics ⇒ 💩 Not Haskell

```
{-# LANGUAGE TemplateHaskell #-}
import Vaporware.Generics.Library
```

```
patch4 :: ΔData
patch4 = \exp ->
  [ RemoveConstructor "For" [(exp,exp,exp),exp]
  , AddConstructor "While" [exp, exp]
  ]

data Exp4 = $(patch_datatype Exp3 patch4)
```

Design 3: Generics ⇒ 💩 Not Haskell

```
{-# LANGUAGE TemplateHaskell #-}
import Vaporware.Generics.Library
```

```
patch4 :: ΔData
patch4 = \exp ->
  [ RemoveConstructor "For" [(exp,exp,exp),exp]
  , AddConstructor "While" [exp, exp]
  ]

data Exp4 = $(patch_datatype Exp3 patch4)
```

```
for2while :: Ast3.Exp
for2while (For (i,c,n) b) =
    i `Seq` While c (b `Seq` n)
for2while _ = $(generate_fold_boilerplate)
```

Design 3: Generics ⇒ 💩 Complicated

```
data Exp1 = ...
data Exp2 = ...
data Exp3 = ...
...
```

```
type Exp =
  $(patch_datatype Ast3.Exp patch4)
```

Minimum contributor **skill level**

Design 3: Generics ⇒ 💩 No Types?

- 🧑‍🔬🔥 Research!

Design 3: Generics ⇒ 💩 No Types?

- 🧑‍🔬🔥 Research!
- 💍 Ornaments

Design 3: Generics ⇒ 💩 No Types?

- 🧑‍🔬🔥 Research!
- 💍 Ornaments
- 🎁 Data type description EDSLs

Design 3: Generics ⇒ 💩 No Types?

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- 📦 Container extension

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- https://personal.cis.strath.ac.uk/conor.mcbride/pub/OAAO/LitOrn.pdf

Design 3: Generics ⇒ 💩 No Types?

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- https://dl.acm.org/doi/pdf/10.1145/2502409.2502413

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Design 3: Generics ⇒ 💩 No Types?

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- https://doi.org/10.1017/S0956796816000356
- ...

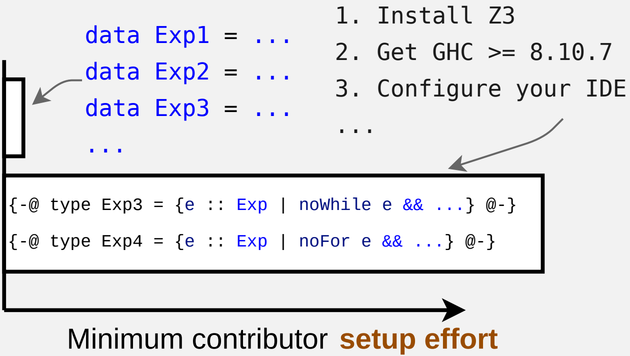
Design 4: One AST, with refinements

LiquidHaskell

```
{-@ type Exp3 = {e :: Exp | noWhile e && ...} @-}
{-@ type Exp4 = {e :: Exp | noFor e && ...} @-}

{-@ for2while :: Exp3 -> Exp4 @-}
for2while :: Exp -> Exp
```

Design 4: One AST, with refinements ⇒ 💩 Not Hs98



Design 5: One AST, with parameters

```
data Exp
  = Raw String
  | If Exp Exp Exp
  | Goto Label
  | Instr SSM.Instr
  | Typed Type Exp
  | For (Exp,Exp,Exp) Exp
  | While Exp Exp
  | ...
```

Design 5: One AST, with parameters

```
data Exp a b c d e f g h ... -- One param per ctr.
  = Raw a String
  | If b Exp Exp Exp
  | Goto c Label
  | Instr d SSM.Instr
  | Typed e Type Exp
  | For f (Exp,Exp,Exp) Exp
  | While g Exp Exp
  | ...
```

Design 5: One AST, with parameters

```
data Exp a b c d e f g h ... -- One param per ctr.
  = Raw a String
  | If b Exp Exp Exp
  | Goto c Label
  | Instr d SSM.Instr
  | Typed e Type Exp
  | For f (Exp,Exp,Exp) Exp
  | While g Exp Exp
  | ...
```

```
for2while :: Exp a b c d e for  while  ...
          -> Exp a b c d e Void ()     ...
```

Design 5: One AST, with parameters

```
data Exp a b c d e f g h ... -- One param per ctr.
  = Raw a String
  | If b Exp Exp Exp
  | Goto c Label
  | Instr d SSM.Instr
  | Typed e Type Exp
  | For f (Exp,Exp,Exp) Exp
  | While g Exp Exp
  | ...
```

```
for2while :: Exp a b c d e for  while  ...
          -> Exp a b c d e Void ()     ...
```

```
printSSMCode  :: Exp ⊥ ⊥ () () ⊥ ⊥ ... -> String
```

Design 5: One AST, with parameters

```
data Exp a b c d e f g h ... -- One param per ctr.
  = Raw a String
  | If b Exp Exp Exp
  | Goto c Label
  | Instr d SSM.Instr
  | Typed e Type Exp
  | For f (Exp,Exp,Exp) Exp
  | While g Exp Exp
  | ...
```

```
for2while :: Exp a b c d e for  while  ...
          -> Exp a b c d e Void ()     ...
```

```
printSSMCode  :: Exp ⊥ ⊥ () () ⊥ ⊥ ... -> String
```

✅ Pattern-checker friendly ✅ Easy re-ordering

Design 5: One AST, with parameters

```
data Exp a b c d e f g h ... -- One param per ctr.
  = Raw a String
  | If b Exp Exp Exp
  | Goto c Label
  | Instr d SSM.Instr
  | Typed e Type Exp
  | For f (Exp,Exp,Exp) Exp
  | While g Exp Exp
  | ...
```

```
for2while :: Exp a b c d e for  while  ...
          -> Exp a b c d e Void ()     ...
```

```
printSSMCode  :: Exp ⊥ ⊥ () () ⊥ ⊥ ... -> String
```

✅ Pattern-checker friendly ✅ Easy re-ordering

💩 Big Types

Design 6: One AST, with parameter + type functions

```
data Exp ζ
  = Raw (XRaw ζ) String
  | If (XIf ζ) Exp Exp Exp
  | Goto (XGoto ζ) Label
  | Instr (XInstr ζ) SSM.Instr
  | Typed (XTyped ζ) Type Exp
  | For (XFor ζ) (Exp,Exp,Exp) E
  | While (XWhile ζ) Exp Exp
  | ...
```

```
-- One type per ctr.
type family XRaw ζ
type family XIf ζ
type family XGoto ζ
type family XInstr ζ
type family XTyped ζ
type family XFor ζ
type family XWhile ζ
```

Design 6: One AST, with parameter + type functions

```
data Exp ζ
  = Raw (XRaw ζ) String
  | If (XIf ζ) Exp Exp Exp
  | Goto (XGoto ζ) Label
  | Instr (XInstr ζ) SSM.Instr
  | Typed (XTyped ζ) Type Exp
  | For (XFor ζ) (Exp,Exp,Exp) E
  | While (XWhile ζ) Exp Exp
  | ...
```

```
-- One type per ctr.
type family XRaw ζ
type family XIf ζ
type family XGoto ζ
type family XInstr ζ
type family XTyped ζ
type family XFor ζ
type family XWhile ζ
```

- "Trees That Grow"
  - In GHC
    - https://gitlab.haskell.org/ghc/ghc/-/wikis/implementing-trees-that-grow
  - Conciser in Agda
    - https://icfp24.sigplan.org/details/tyde-2024-papers/9

Summary

- "Divide & conquer" compiler passes
- Risk of O(№ctrs × №passes) repetition:

`Exp` Constructor	P1	P2	P3	P4	...	Pn
`Raw`	✅	❌	❌	❌	...	❌
`If`	❌	✅	✅	✅	...	❌
`Goto`	❌	❌	❌	❌	...	✅
`Instr`	❌	❌	❌	❌	...	✅
`Typed`	❌	❌	✅	✅	...	❌
`For`	❌	✅	✅	❌	...	❌
`While`	❌	✅	✅	✅	...	❌
⋮	⋮	⋮	⋮	⋮	⋱	⋮

- Motivates advanced data type design