Deriving, transforming, optimizing programs

MPRI 2.4

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Let us be dreamers

An old dream:

- write high-level, abstract, modular code;
- let the compiler produce low-level, efficient code.

"Zero-cost abstraction". (A C++/Rust slogan.)

(Pure) functional prog. languages should lend themselves well to this idea.

- No mutable state. Aliasing not a danger.
  Syntactically obvious where each variable receives its value.
- Equational reasoning.
  Programs denote values. Replace equals with equals.
- Simple, rich language.
  Many transformations easily expressed as rewriting rules.

Perhaps not quite true (do need side effects in some form), but let's see.

Equational reasoning

If two terms t_1 and t_2 are observationally equivalent,

and if we have reason to believe that t_2 is more efficient than t_1,

- or that this rewriting step will enable further optimizations,

then we can optimize a program by replacing t_1 with t_2.

Equality

In a a pure & total language, such as Coq, a term is equal to its value.

Two terms that have the same value are equal.

Equal terms are interchangeable – Leibniz's Principle.

Life in an ideal (mathematical) world. See `DemoEqReasoning`.

Observational equivalence

Fix some notion of "success", e.g. t succeeds iff t computes 42.

- Note that this notion depends on the evaluation strategy.

With respect to this notion of success, or "observation",

t_1 and t_2 are observationally equivalent ($t_1 \simeq t_2$) iff,

for every (well-typed) context C,

$C[t_1]$ succeeds if and only if $C[t_2]$ succeeds.

When is a rewriting step valid?

Is full β a valid law?

$$(\lambda x.t_2)\ t_1 \simeq t_2[t_1/x]$$

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Is full β a valid law?

$$(\lambda x.t_2)\ t_1 \simeq t_2[t_1/x]$$

In a pure & total language, such as Coq, yes. Part of definitional equality.

Under call-by-name, even in the presence of non-termination, yes.

Under call-by-value, in the presence of non-termination or other side effects, no.

full β is invalid under call-by-value

Repeat after me:

full β is invalid under call-by-value

full β is invalid under call-by-value

full β is invalid under call-by-value

After 20+ years, I keep making this mistake from time to time!

$(\lambda x.t_2)\ t_1$ cannot be "simplified" to $t_2[t_1/x]$

let $x = t_1$ in t_2 cannot be "simplified" to $t_2[t_1/x]$

What about call-by-value? β_v

Under call-by-value, in the presence of side effects, full β is invalid.

One must restrict it to the case where t_1 is pure.

$$(\lambda x.t_2)\ t_1 \longrightarrow t_2[t_1/x] \qquad \text{provided } t_1 \text{ is pure}$$

Roughly, a closed term t is pure if there exists a value v such that t reduces to v, independently of the store.

Whether a non-closed term t is closed depends on purity hypotheses about its free variables. E.g., is "$f\ x$" pure? Yes, IF f has no side effects.

As a simple special case, one can use β_v, which is valid:

$$(\lambda x.t_2)\ v_1 \longrightarrow t_2[v_1/x]$$

This follows from the theory of parallel reduction.
See `LambdaCalculusStandardization/pcbv_adequacy`.

When is a rewriting step profitable?

When it is valid, is full β a profitable optimization?

$$(\lambda x.t_2)\ t_1 \longrightarrow t_2[t_1/x]$$

When is a rewriting step profitable?

When it is valid, is full β a profitable optimization?

$$(\lambda x.t_2)\ t_1 \longrightarrow t_2[t_1/x]$$

Under call-by-name, it is safe for time and space,
but can increase code size.

Under call-by-need, if x has multiple occurrences in t_2, or if x occurs under a λ within t_2, then the right-hand side risks repeating the computation of t_1, wasting time and space. This danger exists even if t_1 is a value!

In short, this optimization step seems profitable when x is used "at most once" in t_2, for a suitable definition of this notion.

Turner, Wadler, Mossin, Once upon a type, 1995.

Peyton Jones, Santos, A transformation-based optimiser for Haskell, 1997.

Summary so far

A proposed rewriting rule $t_1 \longrightarrow t_2$ is valid if $t_1 \simeq t_2$ holds.

- This is influenced by the evaluation strategy, the presence or absence of side effects, and type hypotheses.

A proposed rewriting rule $t_1 \longrightarrow t_2$ may or may not be profitable.

- This is influenced by many factors, including further optimizations and transformations.

let-reduction

So far, I have discussed full β versus β_v.

If the language has a primitive construct,
then an analogous discussion applies to "full let" versus let_v.

$$\begin{array}{rcl} \text{let } x = t_1 \text{ in } t_2 & \longrightarrow & t_2[t_1/x] \\ \text{let } x = v_1 \text{ in } t_2 & \longrightarrow & t_2[v_1/x] \end{array}$$

η-reduction and η-expansion

Is this optimization valid?

$$\lambda x.t\ x \simeq t \qquad \text{provided } x \notin fv(t)$$

In a pure & total language, such as Coq, yes. Part of definitional equality.

Under call-by-name, in the presence of non-termination, I think it is...

Under call-by-value, in the presence of side effects, it definitely isn't.

When it is valid, is it profitable? Possibly. E.g., after a naïve CPS transformation, η-reduction turns $\lambda x.k\ x$ into k, which amounts to tail call optimization.

Yet η-reduction can be costly and η-expansion can be profitable. Tricky!

What is inlining?

Inlining is the action of replacing a call to a known function with the suitably instantiated body of this function.

So, is inlining just another name for β_v?

$$(\lambda x.t_2)\ v_1 \longrightarrow t_2[v_1/x]$$

What is inlining?

No. Inlining can be more accurately described by several rewriting rules:

Looking up a definition: (IR1)
$$\text{let } x = v \text{ in } C[x] \longrightarrow \text{let } x = v \text{ in } C[v] \qquad \text{if } x \notin bv(C)$$

Eliminating dead code: (IR2)
$$\text{let } x = v \text{ in } t \longrightarrow t \qquad \text{if } x \notin fv(t)$$

Binding formals to actuals: (IR3)
$$(\lambda x.t_2)\ t_1 \longrightarrow \text{let } x = t_1 \text{ in } t_2$$

These rules are valid under every strategy and in the face of side effects.

Rule IR1 works for every value v, not just λ-abstractions.

Rules IR1 and IR2 work for “let rec”, too!

Rule IR1 duplicates v and can cause non-termination at compile-time (!) or an explosion in code size.

Simplification rules

A few additional simplification rules are useful:

$$
\begin{array}{rcl}
\text{Eliminating an alias:} & (\text{SR1}) & \\
\text{let } y = x \text{ in } t & \longrightarrow & t[x/y] \\
\text{Hoisting a binding:} & (\text{SR2}) & \\
E[\text{let } x = t_1 \text{ in } t_2] & \longrightarrow & \text{let } x = t_1 \text{ in } E[t_2]
\end{array}
$$

These rules are valid under every strategy and in the face of side effects.

Example

Consider this tiny example:

```
let succ x = x + 1
let even x = x mod 2 = 0
let test x = even (succ x)
```

This could be call-by-value (OCaml) or call-by-need (Haskell).

Example, continued

```
let succ x = x + 1
let even x = x mod 2 = 0
let test x = even (succ x)
```

Inlining `succ` and `even` (IR1, applied twice) yields:

```
let succ x = x + 1
let even x = x mod 2 = 0
let test x = (fun x -> x mod 2 = 0) ((fun x -> x + 1) x)
```

Example, continued

```
let succ x = x + 1
let even x = x mod 2 = 0
let test x = (fun x -> x mod 2 = 0) ((fun x -> x + 1) x)
```

Eliminating dead code (IR2, applied twice) yields:

```
let test x = (fun x -> x mod 2 = 0) ((fun x -> x + 1) x)
```

Example, continued

```
let test x = (fun x -> x mod 2 = 0) ((fun x -> x + 1) x)
```

Binding (IR3) yields:

```
let test x = (fun x -> x mod 2 = 0) (let x = x in x + 1)
```

Example, continued

```
let test x = (fun x -> x mod 2 = 0) (let x = x in x + 1)
```

Renaming (SR1) yields:

```
let test x =
  (fun x -> x mod 2 = 0) (x + 1)
```

Example, continued

```
let test x =
  (fun x -> x mod 2 = 0) (x + 1)
```

Binding (IR3) yields:

```
let test x =
  let x = x + 1 in
  x mod 2 = 0
```

Example, continued

```
let test x =
  let x = x + 1 in
  x mod 2 = 0
```

Optionally, one more application of IR1 & IR2 could yield:

```
let test x =
  (x + 1) mod 2 = 0
```

This would not improve the machine code that we get in the end, though.

Case of known constructor

IR3 is the simplification rule that actually saves one step of computation.

It is applicable when a function value is eliminated, that is, called.

What if a value of an algebraic data type is eliminated?

Case of known constructor

IR3 is the simplification rule that actually saves one step of computation.

It is applicable when a function value is eliminated, that is, called.

What if a value of an algebraic data type is eliminated?

A new rule is needed:

Case of known constructor: (IR4)

$$\text{case inj}_i\ v \text{ of } x_1.t_1 \parallel x_2.t_2 \quad \longrightarrow \quad \text{let } x_i = v \text{ in } t_i$$

Example

Suppose Booleans are user-defined:

```
type bool = False | True
```

Now, consider this tiny example:

```
let not x = match x with False -> True | True -> False
let test x = not (not x)
```

Example, continued

```
let not x = match x with False -> True | True -> False
let test x = not (not x)
```

Inlining (IR1, applied twice) and dead code elimination (IR2) yield:

```
let test x =
  (fun x -> match x with False -> True | True -> False)
    ((fun x -> match x with False -> True | True -> False) x)
```

Binding (IR3) and renaming (SR1) yield:

```
let test x =
  (fun x -> match x with False -> True | True -> False)
    (match x with False -> True | True -> False)
```

Example, continued

```
let test x =
  (fun x -> match x with False -> True | True -> False)
    (match x with False -> True | True -> False)
```

Binding (IR3) yields:

```
let test x =
  let x = match x with False -> True | True -> False in
  match x with False -> True | True -> False
```

Example, continued

```
let test x =
  let x = match x with False -> True | True -> False in
  match x with False -> True | True -> False
```

Now, what? The rule β_v is not applicable here.

Example, continued

```
let test x =
  let x = match x with False -> True | True -> False in
  match x with False -> True | True -> False
```

Now, what? The rule β_v is not applicable here.

Under call-by-need, this let construct can be reduced:

```
let test x =
  match
    match x with False -> True | True -> False
  with
    False -> True | True -> False
```

We then seem to need a “case-of-case” simplification rule.

What happens under call-by-value, though?

E of case

Under call-by-value, one could argue that the right-hand side is pure and apply full β.

One can do better and directly apply a new rule:

$$\begin{array}{rcl} \text{E of case:} & & \text{(SR3)} \\ E[\text{case } t \text{ of } x_1.t_1 \parallel x_2.t_2] & \longrightarrow & \text{case } t \text{ of } x_1.E[t_1] \parallel x_2.E[t_2] \end{array}$$

This rule is valid under every strategy. I think.

It is known as a commuting conversion.

Case-of-case is a special case of it!

Exercise (recommended): Write the rule “case-of-case”.

Example, continued

```
let test x =
  let x = match x with False -> True | True -> False in
  match x with False -> True | True -> False
```

By E-of-case (SR3), we obtain:

```
let test x =
  match x with
  | False -> (
      let x = True in
      match x with False -> True | True -> False
    )
  | True  -> (
      let x = False in
      match x with False -> True | True -> False
    )
```

Example, continued

```
let test x =
  match x with
  | False -> (
      let x = True in
      match x with False -> True | True -> False
    )
  | True  -> (
      let x = False in
      match x with False -> True | True -> False
    )
```

Inlining (IR1, IR2) and case-of-known-constructor (IR4) yield:

```
let test x =
  match x with
  | False -> False
  | True  -> True
```

Example, continued

```
let test x =
  match x with
  | False -> False
  | True  -> True
```

Yet another simplification rule, η-reduction for sums, yields:

```
let test x = x
```

Case of case, improved

This rule duplicates the evaluation context:

$$\text{E of case:}\quad (\text{SR3})$$
$$E[\text{case } t \text{ of } x_1.t_1 \parallel x_2.t_2] \quad\longrightarrow\quad \text{case } t \text{ of } x_1.E[t_1] \parallel x_2.E[t_2]$$

This is potentially devastating!

E.g., suppose E is "case [ ] of $y_1.u_1 \parallel y_2.u_2$":

$$\text{Case of case:}\quad (\text{SR3c})$$
$$\text{case (case } t \text{ of } x_1.t_1 \parallel x_2.t_2) \text{ of } y_1.u_1 \parallel y_2.u_2 \quad\longrightarrow$$
$$\begin{array}{r}\text{case } t \text{ of } x_1.(\text{case } t_1 \text{ of } y_1.u_1 \parallel y_2.u_2) \\ \parallel x_2.(\text{case } t_2 \text{ of } y_1.u_1 \parallel y_2.u_2)\end{array}$$

The branches u_1 and u_2 are duplicated! What to do?

Case of case, improved

A solution is to introduce join points to limit duplication.

$$\begin{array}{rr} \text{Case of case, with join points:} & (\text{SR3cj}) \\ \text{case } (\text{case } t \text{ of } x_1.t_1 \parallel x_2.t_2) \text{ of } y_1.u_1 \parallel y_2.u_2 & \longrightarrow \\ \text{let } k_1 = \lambda y_1.u_1 \text{ and } k_2 = \lambda y_2.u_2 \text{ in} & \\ \text{case } t \text{ of } x_1.(\text{case } t_1 \text{ of } y_1.k_1\ y_1 \parallel y_2.k_2\ y_2) & \\ \parallel x_2.(\text{case } t_2 \text{ of } y_1.k_1\ y_1 \parallel y_2.k_2\ y_2) & \end{array}$$

The names k_1 and k_2 can be thought of as labels to which one jumps.

We have intentionally allowed the outer case to be duplicated. The two copies scrutinize t_1 and t_2, so further simplifications should be possible.

Example

Suppose the function `bor` implements Boolean disjunction. Consider this:

```
match bor b1 b2 with
| False -> <foo>
| True  -> <bar>
```

Inlining yields:

```
match
  match b1 with False -> b2 | True -> True
with
| False -> <foo>
| True  -> <bar>
```

Example, continued

```
match
  match b1 with False -> b2 | True -> True
with
| False -> <foo>
| True  -> <bar>
```

Applying rule SR3cj yields:

```
let foo () = <foo>
and bar () = <bar> in
match b1 with
| False -> (match b2   with False -> foo() | True -> bar())
| True  -> (match True with False -> foo() | True -> bar())
```

Example, continued

```
let foo () = <foo>
and bar () = <bar> in
match b1 with
| False -> (match b2   with False -> foo() | True -> bar())
| True  -> (match True with False -> foo() | True -> bar())
```

By case-of-known-constructor (IR4), we obtain:

```
let foo () = <foo>
and bar () = <bar> in
match b1 with
| False -> (match b2   with False -> foo() | True -> bar())
| True  -> bar()
```

Example, continued

```
let foo () = <foo>
and bar () = <bar> in
match b1 with
| False -> (match b2 with False -> foo() | True -> bar())
| True  -> bar()
```

Because there is only one jump to `foo`, it can be inlined:

```
let bar () = <bar> in
match b1 with
| False -> (match b2 with False -> <foo> | True -> bar())
| True  -> bar()
```

Example, continued

`bar` is a "join point", a local function that is meant to represent a code label.

It is always called via a tail call.

The idea is, it should not require a closure allocation.

```
let bar () = <bar> in
match b1 with
| False -> (match b2 with False -> <foo> | True -> bar())
| True  -> bar()
```

It must not be naïvely inlined: that would cause duplication again!

During further transformations, one should ensure that it remains a "join point" and is not inadvertently turned into a full-fledged first-class function.

Maurer, Ariola, Downen, Peyton Jones, Compiling without continuations, 2017.

Redundant case elimination

Can we optimize this code?

```
match xs with
| []        -> []
| y :: ys ->
    match xs with
    | []        -> <foo>
    | z :: zs -> <bar>
```

The rules shown so far can simplify this only if there is a binding of the form `let xs = <value>` higher up. This is case-of-known-constructor.

Redundant case elimination

Can we optimize this code?

```
match xs with
| []       -> []
| y :: ys ->
    match xs with
    | []       -> <foo>
    | z :: zs -> <bar>
```

The rules shown so far can simplify this only if there is a binding of the form `let xs = <value>` higher up. This is case-of-known-constructor.

We could insert `let xs = y :: ys` at line 4,
but that would be potentially pessimizing.

Better keep track of which equations are known at each program point, and improve case-of-known-constructor to exploit these equations.

See Peyton Jones and Marlow, §6.3.

Inlining recursive functions

The rule IR1, as stated, does not allow inlining a function into itself. This could be relaxed.

Inlining a recursive function into itself amounts to loop unrolling.

Inlining a recursive function at its call site amounts to loop peeling.

Summary

An old idea. Particularly important in very high-level languages.

It eliminates the function call overheard, and enables other optimizations.

The danger of inlining is an increase in code size and potential non-termination at compile time. This must be controlled via heuristics or via user annotations (partial evaluation; staging).

Aggressive inliners can be guided by program analyses.

Peyton Jones, Santos, A transformation-based optimiser for Haskell, 1997.

Peyton Jones, Marlow, Secrets of the Glasgow Haskell Compiler inliner, 2002.

Jagannathan and Wright, Flow-directed inlining, 1996.

Example

Here is a reasonably elegant way of obtaining the last element of a list:

```
let rec last xs =
  match xs with
  |            [] -> assert false
  |           [x] -> x
  | _ :: x :: xs -> last (x :: xs)
```

Unfortunately, it is inefficient...

Example

Here is a reasonably elegant way of obtaining the last element of a list:

```
let rec last xs =
  match xs with
  |           [] -> assert false
  |          [x] -> x
  | _ :: x :: xs -> last (x :: xs)
```

Unfortunately, it is inefficient...

- The cell `x1 :: xs` is re-allocated; CSE can recognize and avoid this.
- Two list cells are inspected to find that the third branch must be taken.

Every cell is tested twice! We forget information through the recursive call.

How would you remedy this (by hand)?

Example, hand-optimized

By hand, one might write this optimized code:

```
let rec last xs =
  match xs with
  |       [] -> assert false
  | x :: xs -> last_cons x xs

and last_cons x xs =
  match xs with
  |       [] -> x
  | x :: xs -> last_cons x xs
```

`last_cons` is a loop with two registers `x` and `xs`.

Keeping track of `x` does the trick. Each list cell is examined once.

Call-pattern specialization

Could a compiler do this automatically?

Inlining `last` into itself would amount to loop unrolling (i.e., doing two iterations at a time) but would not eliminate the problem entirely.

The problem lies in the call `last (x :: xs)`, where information is lost.

We must specialize `last` for this call pattern.

Example, optimized

The first step is to create a specialized function, `last_cons`.

```
let rec last xs =
  match xs with
  |            [] -> assert false
  |           [x] -> x
  | _ :: x :: xs -> last (x :: xs)

and last_cons x xs =
  last (x :: xs)
```

The equation `last (x :: xs) = last_cons x xs` holds (obviously).

We record (remember) this equation for later use.

Example, optimized

The second step is to inline `last` into `last_cons`.

```
let rec last xs =
  match xs with
  |            [] -> assert false
  |           [x] -> x
  | _ :: x :: xs -> last (x :: xs)

and last_cons x xs =
  let xs = x :: xs in
  match xs with
  |            [] -> assert false
  |           [x] -> x
  | _ :: x :: xs -> last (x :: xs)
```

Example, optimized

By inlining `xs` and exploiting case-of-known-constructor, we get:

```
let rec last xs =
  match xs with
  |           [] -> assert false
  |          [x] -> x
  | _ :: x :: xs -> last (x :: xs)

and last_cons x xs =
  match xs with
  |       [] -> x
  | x :: xs -> last (x :: xs)
```

What should be the last step?

Example, optimized

The last step is to replace `last (x :: xs)` with `last_cons x xs`.

There are two occurrences, one of which lies within `last_cons` itself.

We get the code that we would have written, with one iteration unrolled:

```
let rec last xs =
  match xs with
  |            [] -> assert false
  |           [x] -> x
  | _ :: x :: xs -> last_cons x xs

and last_cons x xs =
  match xs with
  |      [] -> x
  | x :: xs -> last_cons x xs
```

This exploits an equation that was recorded earlier.

Danger!

The correctness of exploiting an equation within itself is nonobvious.

Recall this situation:

```
let rec last xs =
  match xs with
  |            [] -> assert false
  |           [x] -> x
  | _ :: x :: xs -> last (x :: xs)

and last_cons x xs =
  last (x :: xs)
```

The equation `last (x :: xs) = last_cons x xs` holds (obviously).

There are two places where it can be used right now... What if we did so?

Danger!

We get a non-terminating version of the loop:

```
let rec last xs =
  match xs with
  |           [] -> assert false
  |          [x] -> x
  | _ :: x :: xs -> last_cons x xs

and last_cons x xs =
  last_cons x xs
```

This “obviously correct” transformation is actually incorrect.

We have in fact rolled the loop so it jumps to itself after 0 iterations!

Exploiting $x = v$ within itself leads to $x = x$, which is nonsensical.

Summary

Call-pattern specialization is also known as constructor specialization.

It is simple, but runs a risk of generating uninteresting specializations and a risk of nontermination at compile-time. Heuristics are needed.

Peyton Jones, Call-pattern specialisation for Haskell programs, 2007.

Deforestation

Programs expressed in a high-level style often build intermediate data structures (lists, trees, ...) which are immediately used and discarded.

They typically allow communication between a producer and a consumer.

Deforestation (Wadler, 1990) aims to get rid of them.

Example

The composition of `filter` and `map` allocates an intermediate list.

As a direct attempt at deforestation, let us try and optimize it.

```
let bar p f xs =
  List.filter p (List.map f xs)
```

Let us specialize for the call pattern `List.filter p (List.map f xs)`...

I am using an expression as a call pattern – this goes beyond GHC.

Example

After creating a specialized copy
and inlining `List.filter` and `List.map` into it, we get:

```
let filter_map p f xs =
  match
    match xs with
    | [] -> []
    | x :: xs -> f x :: List.map f xs
  with
  | [] -> []
  | x :: xs ->
      if p x then x :: List.filter p xs
      else List.filter p xs

let bar p f xs =
  filter_map p f xs
```

Example

Performing case-case conversion yields:

```
let filter_map p f xs =
  match xs with
  | [] -> []
  | x :: xs ->
      let x :: xs = f x :: List.map f xs in
      if p x then x :: List.filter p xs
      else List.filter p xs
```

Example

Deciding that `e1 :: e2` is evaluated from left-to-right, we get:

```
let filter_map p f xs =
  match xs with
  | [] -> []
  | x :: xs ->
      let x = f x in
      let xs = List.map f xs in
      if p x then x :: List.filter p xs
      else List.filter p xs
```

Evaluation order is left undecided by OCaml.

Example

We wisely choose to inline `xs`, as it is used only once (in each branch):

```
let filter_map p f xs =
  match xs with
  | [] -> []
  | x :: xs ->
      let x = f x in
      if p x then x :: List.filter p (List.map f xs)
      else List.filter p (List.map f xs)
```

This is full β!

It is valid under call-by-need. (Assuming no side effects but divergence.)

It is invalid under call-by-value (with side effects), unless `f` is pure.

- `f` must not read or write mutable data, and must terminate.

The OCaml compiler won't do this!

Example

We now recognize the call pattern `List.filter p (List.map f xs)`.

```
let rec filter_map p f xs =
  match xs with
  | [] -> []
  | x :: xs ->
      let x = f x in
      if p x then x :: filter_map p f xs
      else filter_map p f xs
```

We get the code that an OCaml programmer would write by hand.

No intermediate list! Successful deforestation.

Summary

The equation `List.filter p (List.map f xs) = filter_map p f xs`

- holds under call-by-need;
- holds under call-by-value (with side effects) if `f` is pure.

Pure languages offer greater potential for aggressive optimization!

Idea 1: focus on lists

Focus on lists, a universal type for exchanging sequences of elements.

Some functions are list producers; some are list consumers.

Some, such as `filter` and `map`, are both. (Not a problem.)

Some, such as `zip` and `unzip` have two inputs or two outputs.

Composing these functions yields producer-consumer pipelines.

Idea 2: use a custom internal data format

Producers and consumers use lists as an exchange format.

They can work internally using a different data representation.

They are then be wrapped in conversions to and from lists.

When a producer and consumer are composed,

- two conversions, to and from lists, should cancel out,
- so there remains to optimize a composition at the internal data type.

This is an instance of the worker/wrapper transformation.

Gill and Hutton, The worker/wrapper transformation, 2009.

Idea 3: avoid recursion

The internal data format should have a nonrecursive type, so that:

- Most producers and consumers are not recursive!
- At least one of the conversions, to and from lists, must be recursive.

Two approaches, based on two internal data formats, have been proposed:

- shortcut deforestation, based on folds;
- stream fusion, based on streams.

Gill, Launchbury, Peyton Jones, A short cut to deforestation, 1993.

Coutts, Leshchinskiy, Stewart, Stream fusion: from lists to streams to nothing at all, 2007.

The internal data format

In shortcut deforestation, a sequence is internally represented as a fold.

A fold is a function that allows traversing the sequence.

```
type 'a fold =
  { fold: 'b. ('a -> 'b -> 'b) -> 'b -> 'b }
```

It is a producer which pushes elements towards a consumer.

This is the standard Church encoding of lists.

Gill et al.'s paper does not explicitly use the above polymorphic type.
I follow them.

Converting a list to a fold

This is OCaml's `List.fold_right`, with the last two parameters swapped:

```
let rec foldr c n xs =
  match xs with
  |       [] -> n
  | x :: xs -> c x (foldr c n xs)
```

If `xs` is a list then `fun c n -> foldr c n xs` is the corresponding fold.

We could define:

```
let import (xs : 'a list) : 'a fold =
  { fold = fun c n -> foldr c n xs }
```

Converting a fold to a list

To convert a fold to a list, we apply it to “cons” and “nil”:

```
let build g =
  g (fun x xs -> x :: xs) []
```

We could define:

```
let export ({ fold } : 'a fold) : 'a list =
  build fold
```

Isomorphism

The idea is that we have an isomorphism between lists and (certain well-behaved) folds.

The following law holds:

- `export (import xs)` is observationally equivalent to `xs`.

The reverse law holds if `f` is pure and terminating:

- `import (export f)` is equivalent to `f`.

Naturally, the law that's needed when composing two components is...

Isomorphism

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Naturally, the law that's needed when composing two components is...

...the second one.

Let's just pretend that it holds unconditionally.

Challenge: formalize build/foldr in Coq and establish the isomorphism.

Isomorphism

In Gill et al.'s paper, the second law is known as "the foldr/build rule":

```
foldr c n (build g) = g c n
```

An example consumer-and-producer

In the list library, `map` is written as follows:

```
let map f xs =
  build (fun c n ->
    foldr (fun x xs -> c (f x) xs) n xs
  )
```

The list `xs` is imported using `foldr`, yielding a fold.

A new fold is then constructed on top of it.

This new fold is converted back to a list using `build`.

An example consumer-and-producer

Similarly, `filter` is written as follows:

```
let filter p xs =
  build (fun c n ->
    foldr (fun x xs -> if p x then c x xs else xs) n xs
  )
```

Back to (filter; map)

What happens when we compose `filter` and `map`?

```
let bar p f xs =
  filter p (map f xs)
```

Back to (filter; map)

Inlining `filter` and `map` yields:

```
let bar p f xs =
  build (fun c n ->
    foldr
      (fun x xs -> if p x then c x xs else xs)
      n
      (build (fun c n ->
        foldr (fun x xs -> c (f x) xs) n xs
      ))
  )
```

We recognize `foldr _ _ (build _)`.

Back to (filter; map)

Exploiting the equation `foldr c n (build g) = g c n` yields:

```
let bar p f xs =
  build (fun c n ->
    let c x xs = if p x then c x xs else xs in
    foldr (fun x xs -> c (f x) xs) n xs
  )
```

This is where we save an intermediate list.

Back to (filter; map)

Inlining `c` yields:

```
let bar p f xs =
  build (fun c n ->
    foldr (fun x xs ->
      let x = f x in
      if p x then c x xs else xs
    ) n xs
  )
```

This is where `filter` and `map` come into contact and combine.

Back to (filter; map)

We are essentially finished, but can work a little more.

Inlining `build` yields:

```
let bar p f xs =
  foldr (fun x xs ->
    let x = f x in
    if p x then x :: xs else xs
  ) [] xs
```

Back to (filter; map)

Call-pattern specialization for `foldr` yields:

```
let rec filter_map p f xs =
  match xs with
  | [] -> []
  | x :: xs ->
      let xs = filter_map p f xs in
      let x = f x in
      if p x then x :: xs else xs

let bar p f xs =
  filter_map p f xs
```

Assuming the language is pure,
or assuming `p` and `f` are pure, we can inline `xs`...

Back to (filter; map)

Inlining `xs` yields:

```
let rec filter_map p f xs =
  match xs with
  | [] -> []
  | x :: xs ->
      let x = f x in
      if p x then x :: filter_map p f xs
      else filter_map p f xs
```

We again get the code that an OCaml programmer would write by hand.

The internal data format

In stream fusion, a sequence is internally represented as a stream.

A stream is a function that allows querying the sequence.

```
type 'a stream =
  | S:
      (* If you have a pair of a producer function... *)
      ('s -> ('a, 's) step)
      (* ...and an initial state, *)
      * 's ->
      (* then you have a stream. *)
      'a stream
```

It is a producer from which a consumer can pull elements.

A typical object-oriented idiom, analogous to Java iterators, but not inherently mutable.

This is an existential type, very much like the type of closures in week 3.

The internal data format

Querying a stream produces a result of the following form:

```
type ('a, 's) step =
  | Done               (* finished *)
  | Yield of 'a * 's   (* an element and a new state *)
  | Skip of 's         (* just a new state – please ask again *)
```

The types `stream` and `step` are nonrecursive.

This, and the existence of `Skip`, allows most stream producers to be nonrecursive functions.

A consumer must ask, ask, ask until a non-`Skip` result is produced.

Converting a list to a stream

This conversion function is nonrecursive:

```
let stream (xs : 'a list) : 'a stream =
  let next xs =
    match xs with
    |       [] -> Done
    | x :: xs -> Yield (x, xs)
  in
  S (next, xs)
```

Exercise: Here, what is the type `'s` of states?

Converting a list to a stream

The local function `next` is in fact closed, so one can also write:

```
let stream_next xs =
  match xs with
  |       [] -> Done
  | x :: xs -> Yield (x, xs)

let stream (xs : 'a list) : 'a stream =
  S (stream_next, xs)
```

Converting a stream to a list

This is a recursive consumer function:

```
let unstream (S (next, s) : 'a stream) : 'a list =
  let rec unfold s =
    match next s with
    | Done          -> []
    | Yield (x, s) -> x :: unfold s
    | Skip s        -> unfold s
  in
  unfold s
```

Isomorphism

There is an isomorphism between lists and (certain) streams.

The following law holds:

- `unstream (stream xs)` is observationally equivalent to `xs`.

The reverse law holds if `str` is pure and terminating:

- `stream (unstream str)` is equivalent to `str`.

Again, we need the second law, known as “stream/unstream”.

Let’s pretend that it holds unconditionally.

Examples of stream producers

How would you implement a singleton stream?

Examples of stream producers

How would you implement a singleton stream?

```
let return (x : 'a) : 'a stream =
  let next s =
    if s then Yield (x, false) else Done
  in
  S (next, true)
```

The type of `s` is `bool`: either we have already yielded an element, or we have not.

Each stream producer freely chooses its type of internal states.

Exercise: Write `interval` of type `int -> int -> int stream`.

Exercise: Write `append` of type `'a stream -> 'a stream -> 'a stream`.

An example consumer-and-producer

Here is `map` on streams, known as `S.map` in the following:

```
let map (f : 'a -> 'b) (S(next, s) : 'a stream) : 'b stream =
  let next s =
    match next s with
    | Done          -> Done
    | Yield (x, s) -> Yield (f x, s)
    | Skip s        -> Skip s
  in
  S (next, s)
```

Again, not a recursive function!

An example consumer-and-producer

Composing with conversions to and from streams yields `map` on lists:

```
let map (f : 'a -> 'b) (xs : 'a list) : 'b list =
  unstream (S.map f (stream xs))
```

An example consumer-and-producer

Here is `filter` on streams, known as `S.filter` in the following:

```
let filter (p : 'a -> bool) (S (next, s) : 'a stream) =
  let next s =
    match next s with
    | Done          -> Done
    | Yield (x, s) -> if p x then Yield (x, s) else Skip s
    | Skip s        -> Skip s
  in
  S (next, s)
```

Again, not a recursive function!

An example consumer-and-producer

Composing with conversions to and from streams yields `filter` on lists:

```
let filter (p : 'a -> bool) (xs : 'a list) : 'a list =
  unstream (S.filter p (stream xs))
```

Back to (filter; map)

What happens when we compose `filter` and `map`?

```
let bar p f xs =
  L.filter p (L.map f xs)
```

Back to (filter; map)

Inline `filter` and `map`:

```
let bar p f xs =
  unstream (S.filter p (stream (
    unstream (S.map f (stream xs))
  )))
```

Back to (filter; map)

Use the stream/unstream rule:

```
let bar p f xs =
  unstream (S.filter p (S.map f (stream xs)))
```

`S.filter` and `S.map` come in contact.

Let's inline the hell out of this code!

Back to (filter; map)

Inline `stream`:

```
let bar p f xs =
  unstream (S.filter p (S.map f (S (stream_next, xs))))
```

Back to (filter; map)

Inline `S.map`:

```
let bar p f xs =
  let next s =
    match stream_next s with
    | Done          -> Done
    | Yield (x, s) -> Yield (f x, s)
    | Skip s        -> Skip s
  in
  unstream (S.filter p (S (next, xs)))
```

Back to (filter; map)

Inline `stream_next`:

```
let bar p f xs =
  let next s =
    match
      match s with
      |      [] -> Done
      | x :: s -> Yield (x, s)
    with
    | Done          -> Done
    | Yield (x, s) -> Yield (f x, s)
    | Skip s        -> Skip s
  in
  unstream (S.filter p (S (next, xs)))
```

Back to (filter; map)

Perform case-of-case conversion, followed with case-of-constructor:

```
let bar p f xs =
  let next s =
    match s with
    |      [] -> Done
    | x :: s -> Yield (f x, s)
  in
  unstream (S.filter p (S (next, xs)))
```

Back to (filter; map)

Inline `S.filter`:

```
let bar p f xs =
  let next s =
    match s with
    |      [] -> Done
    | x :: s -> Yield (f x, s)
  in
  let next s =
    match next s with
    | Done          -> Done
    | Yield (x, s) -> if p x then Yield (x, s) else Skip s
    | Skip s        -> Skip s
  in
  unstream (S (next, xs))
```

Back to (filter; map)

Inline the first `next` function into the second one:

```
let bar p f xs =
  let next s =
    match
      match s with
      |      [] -> Done
      | x :: s -> Yield (f x, s)
    with
    | Done          -> Done
    | Yield (x, s) -> if p x then Yield (x, s) else Skip s
    | Skip s        -> Skip s
  in
  unstream (S (next, xs))
```

Back to (filter; map)

Apply case-of-case and case-of-constructor again:

```
let bar p f xs =
  let next s =
    match s with
    |      [] -> Done
    | x :: s ->
        let y = f x in if p y then Yield (y, s) else Skip s
  in
  unstream (S (next, xs))
```

Back to (filter; map)

Inline `unstream`:

```
let bar p f xs =
  let next s =
    match s with
    |      [] -> Done
    | x :: s ->
        let y = f x in if p y then Yield (y, s) else Skip s
  in
  let rec unfold s =
    match next s with
    | Done          -> []
    | Yield (x, s) -> x :: unfold s
    | Skip s        -> unfold s
  in
  unfold xs
```

Back to (filter; map)

Inline `next` into `unstream`:

```
let bar p f xs =
  let rec unfold s =
    match
      match s with
      |     [] -> Done
      | x :: s ->
          let y = f x in if p y then Yield (y, s) else Skip s
    with
    | Done          -> []
    | Yield (x, s) -> x :: unfold s
    | Skip s        -> unfold s
  in
  unfold xs
```

Back to (filter; map)

Apply case-of-case again, then a couple rules, then case-of-constructor:

```
let bar p f xs =
  let rec unfold s =
    match s with
    |      [] -> []
    | x :: s ->
        let y = f x in
        if p y then y :: unfold s else unfold s
  in
  unfold xs
```

Exercise: Clarify which rewriting rules are used here.

Back to (filter; map)

(Optional.) Hoist `unfold` out. (This is λ-lifting.)

```
let rec unfold p f s =
  match s with
  |     [] -> []
  | x :: s ->
      let y = f x in
      if p y then y :: unfold p f s
      else unfold p f s

let bar p f xs =
  unfold p f xs
```

We get the code that an OCaml programmer would write by hand.

No intermediate data structure! Successful deforestation again.

What's the point?

Why is stream fusion preferable to shortcut deforestation?

Shortcut deforestation cannot express `foldl` in a nice way.

Exercise: Implement `foldl` on streams, then on lists.

Exercise: Find out how `foldl (+) 0 (append xs ys)` is optimized.
You should reach a sequence of two loops – no memory allocation.

The way of the future?

Do not let the compiler's heuristics decide
which reductions and simplifications should take place at compile time.

Instead, give explicit staging annotations to distinguish
pipeline-construction-time computation and pipeline-runtime computation!

> *Relying on a general-purpose compiler for library optimization is slippery. [...] A compiler offers no guarantee that optimization will be successfully applied. [...] An innocuous change to a program [can] make it much slower.*

Kiselyov, Biboudis, Palladinos, Smaragdakis,
Stream fusion, to completeness, 2017.

Program derivation

Equational reasoning can be used not just by compilers, but also by programmers, by hand.

Starting from a simple, inefficient program, derive efficient code via a series of rewriting steps.

See my blog post on a derivation of Knuth-Morris-Pratt.

Supercompilation can do this, too!

Secher and Sørensen, On Perfect Supercompilation, 1999.

A few things to remember

- Equational reasoning can be a powerful means of transforming or deriving programs.
- λ-calculus-based (intermediate) languages allow expressing a wide range of program transformations and optimizations.
- Side effects (non-termination, mutable state...) complicate matters.