Compiler Construction

Lecture 13: optimisation

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Optimisation

What's an optimisation?

A compiler optimisation changes the code generated for a program to:

- improve its space usage
- reduce its size
- introduce parallelism
- reduce energy usage
- reduce allocation
- improve locality
- reduce stack usage
- (etc.)

Optimisations preserve program semantics, but improve program pragmatics.

What does it mean to preserve program semantics?

Which optimisations are valid?

An optimisation is **valid** if its input and output have **equivalent semantics**.

We might use the definition of equivalence from *Semantics* (slide 256):

We say that typed L3 programs $\begin{array}{c}\Gamma \vdash e_1 : T\\ \Gamma \vdash e_2 : T\end{array}$ are **contextually equivalent** if

for every context C such that $\begin{array}{c}\cdot \vdash C[e_1] : \mathit{unit}\\ \cdot \vdash C[e_2] : \mathit{unit}\end{array}$ we have either

1. $\begin{array}{l}\langle C[e_1], \{\}\rangle \longrightarrow^{\omega}\\ \langle C[e_2], \{\}\rangle \longrightarrow^{\omega}\end{array}$
2. for some $\begin{array}{c}s_1\\ s_2\end{array}$ we have $\begin{array}{l}\langle C[e_1], \{\}\rangle \rightarrow \langle \mathbf{skip}, s_1\rangle\\ \langle C[e_2], \{\}\rangle \rightarrow \langle \mathbf{skip}, s_2\rangle\end{array}$

(Note: as we shall see, optimisations can actually *reduce* the set of possible behaviours of a program)

What does it mean to preserve program semantics?

The definition of contextual equivalence needs adjustment for larger languages.

For example, it makes all non-terminating programs equal, regardless of effects.

This is not what we want: consider

```
let rec repeat_say msg =
  print_endline msg;
  repeat_say ()

let () = say "Hello"
```

```
let rec repeat_say msg =
  print_endline msg;
  repeat_say ()

let () = say "Goodbye"
```

We'll use the following (very informal) definition:

An optimisation is valid if the output program has
- the same effects
- the same termination behaviour .
- the same return value.

Quiz: valid or invalid?

Are the following optimisations valid in general?

```
let _ = g 2 in f 3  ⤳  f 3

let x = g 2 in f 3 + x  ⤳  f 3 + g 2

map f (map g l)  ⤳  map (fun x → f (g x)) l

if true then e1 else e2  ⤳  e1

let rec loop () = loop () in          let rec loop () = loop () in
  (loop(); print_endline "done")  ⤳    (loop(); ())

fold_right f l u  ⤳  fold_left (fun x y → f y x) u (rev l)
```

Quiz: valid or invalid?

Are the following optimisations valid in general?

```
let _ = g 2 in f 3   ⇝   f 3
```

invalid: `g 2` may perform effects

```
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```

```
map f (map g l)   ⇝   map (fun x → f (g x)) l
```

```
if true then e1 else e2   ⇝   e1
```

```
let rec loop () = loop () in          ⇝   let rec loop () = loop () in
  (loop(); print_endline "done")            (loop(); ())
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```
fold_right f l u   ⇝   fold_left (fun x y → f y x) u (rev l)
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let rec loop () = loop () in            let rec loop () = loop () in
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Quiz: valid or invalid?

Optimisation
● ● ● ●

Specialisation

Other optimisations

Undefined behaviour

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```

depends on the order of operand evaluation

```
map f (map g l)  ⇝  map (fun x → f (g x)) l
```

```
if true then e1 else e2  ⇝  e1
```

```
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  (loop(); print_endline "done")         (loop(); ())
```

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`map f (map g l)` ⇝ `map (fun x → f (g x)) l`

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invalid if `f` and `g` perform (non-commuting) effects

`if true then e1 else e2` ⇝ `e1`

```
let rec loop () = loop () in
  (loop(); print_endline "done")
```
⇝
```
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  (loop(); print_endline "done")
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```
let rec loop () = loop () in
  (loop(); print_endline "done")
```

⇝

```
let rec loop () = loop () in
  (loop(); ())
```

valid

`fold_right f l u` ⇝ `fold_left (fun x y → f y x) u (rev l)`

valid

Specialisations

Inlining: examples

Inlining replaces a variable with its definition (typically a function):

```
let succ x = x + 1
let f = map (fun y → succ y)
          [1;2;3]
```

inline →

```
let succ x = x + 1
let f = map (fun y → y + 1)
          [1;2;3]
```

Note: care with free variables is needed:

```
let f y =
 let addy x = x + y in
  map (fun y → addy y) [1;2;3]
```

inline →

```
let f y =
 let addy x = x + y in
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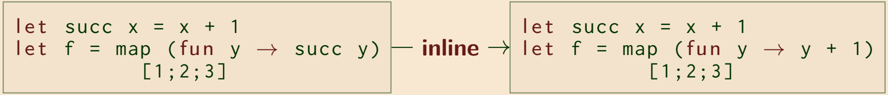
```

Inlining: examples

Inlining replaces a variable with its definition (typically a function):



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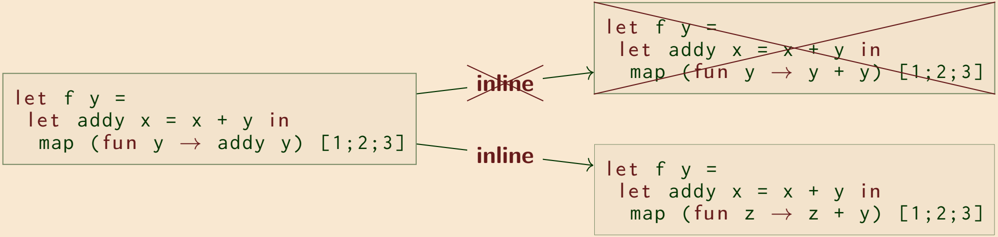


```
let f y =
 let addy x = x + y in
  map (fun y → addy y) [1;2;3]
```

~~inline~~ →

~~let f y =~~
~~let addy x = x + y in~~
~~map (fun y → y + y) [1;2;3]~~

inline →

```
let f y =
 let addy x = x + y in
  map (fun z → z + y) [1;2;3]
```

Inlining: questions

Inlining is an enabling transformation that exposes optimisation opportunities.

Inlining can sometimes be a pessimisation. Questions to consider in each case:

- Does inlining duplicate code?
- Does inlining duplicate work?
- Does inlining expose further optimisation opportunities?

Note: inlining recursive bindings is significantly harder.

Lots of details:

Secrets of the Glasgow Haskell Compiler inliner (1999)
Simon Peyton Jones and Simon Marlow

Monomorphisation (MLton)

Monomorphisation replaces
parameterised types with unparameterised types
polymorphic functions with monomorphic functions
.

```
type 'a t = T of 'a
let f (x: 'a) = T x
let a = f 1
let b = f 2
let z = f (3, 4)
```

— **monomorphise** →

```
type t1 = T1 of int
type t2 = T2 of int * int
let f1 (x: int) = T1 x
let f2 (x: int * int) = T2 x
let a = f1 1
let b = f1 2
let z = f2 (3, 4)
```

Monomorphisation: benefits

Monomorphisation is also an enabling transformation.
The compiler can subsequently specialise representations, e.g. flattening tuples:

`int * (float * bool)` —— **flatten** ——→ `int * float * bool`

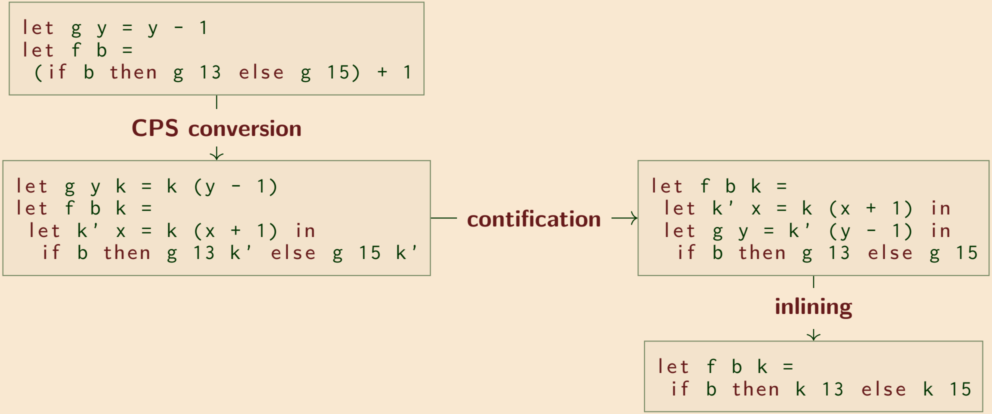
Monomorphisation is used in Mlton, a whole-program-optimising ML compiler:

> *Whole-Program Compilation in MLton (2006)*
> *Stephen Weeks*

Contification

Contification turns a function into a continuation.

Contification applies when a function is always passed the same continuation.



```
let g y = y - 1
let f b =
 (if b then g 13 else g 15) + 1
```

CPS conversion

```
let g y k = k (y - 1)
let f b k =
 let k' x = k (x + 1) in
  if b then g 13 k' else g 15 k'
```

contification

```
let f b k =
 let k' x = k (x + 1) in
 let g y = k' (y - 1) in
  if b then g 13 else g 15
```

inlining

```
let f b k =
 if b then k 13 else k 15
```

Contification in MLton

Contification is also used in Mlton:

Contification Using Dominators (2001)
Matthew Fluet Stephen Weeks

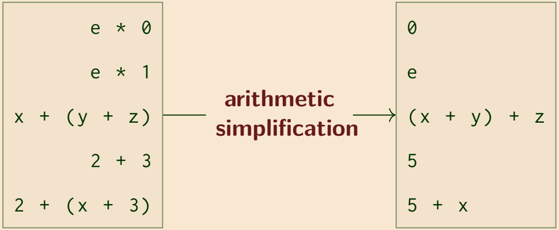
where it was found to

- have minimal effects on compile-time (2–4%)
- significantly reduce run-time (up to 86%)
- reduce executable size (up to 12%)

.

Other optimisations

Arithmetic simplification



arithmetic simplification

`e * 0`	`0`
`e * 1`	`e`
`x + (y + z)`	`(x + y) + z`
`2 + 3`	`5`
`2 + (x + 3)`	`5 + x`

Inlining may expose opportunities for arithmetic simplification.

Care needed: `e * 0` ⇝ `0` only valid if `e` has no effects.

Care needed: very few arithmetic laws apply to floating-point numbers.

Tail-recursion modulo cons: motivation

Observation: It is difficult to implement `map` entirely satisfactorily:

Naive

```
let rec map f l =
match l with
| [] → []
| x :: xs →
  f x::map f xs
```

May run out of stack

CPS

```
let rec map f l k =
match l with
| [] → k []
| x :: xs →
  f x (fun hd →
  map f xs (fun tl →
  k (hd::tl)))

let map f l =
  map f l (fun x → x)
```

Allocates frames on the heap

Accumulator

```
let rec map f l acc =
match l with
| [] → rev acc
| x :: xs →
  map f xs (f x::acc)

let map f l = map f l []
```

Traverses the list twice

Tail-recursion modulo cons: destination passing style

The **TRMC** optimisation transforms functions into **destination-passing style**:

Naive

```
let rec map f l =
match l with
| [] → []
| x :: xs →
  f x::map f xs
```

TRMC →

Destination-passing style

```
let rec map f = function
| [] → []
| x::xs → let y = f x in
          let dst = y :: <Hole> in
          map_dps dst 1 f xs;
          dst
and map_dps dst i f = function
| [] →
  dst.i <- []
| x::xs → let y = f x in
          let dst' = y :: <Hole> in
          dst.[i] <- dst';
          map_dps dst' 1 f xs
```

Idea: allocate a partially-constructed cons cell with an uninitialized tail.
Pass the cons cell (the “destination”) to recursive calls.
Write the result of each call to the tail field of the destination.

Optimisations and undefined behaviour

Optimising programs with undefined behaviour

Our optimisation correctness criterion is based on the behaviour of programs.

What optimisations are justified when a program's behaviour is undefined?

Two principles:

1. There are no constraints on the behaviour of programs with undefined behaviour.
2. A compiler can therefore assume that programs do not have undefined behaviour.

Consequently, optimisation can change the observed behaviour of ill-defined programs.

Integer overflow

sum.c

```
#include <stdio.h>
#include <limits.h>

int sum_range(int start, int len) {
  int total = 0;
  for (int i = start; i <= start + len; i += 1) total += i;
  return total;
}

int main() {
  printf("%d %d\n", sum_range(10, 10), sum_range(INT_MAX-1, 2));
}
```

Without optimisation

```
$ clang -o sum sum.c
$ ./sum
165 0
```

With optimisation

```
$ clang -O3 -o sum sum.c
$ ./sum
165 2147483646
```

(Adapted from an example by Taras Tsugrii)

Integer overflow: what is going on?

sum.c (excerpt)

```
int sum_range(int start, int len) {
  int total = 0;
  for (int i = start; i <= start + len; i += 1) total += i;
  return total;
}
```

Some reasoning about arithmetic justifies a significant optimisation:

$$\begin{aligned} & \text{sum\_range(start,len)} \\ \equiv\ & \text{start} + (\text{start} + 1) + \ldots + (\text{start} + \text{len}) \\ \equiv\ & \text{start} \times (\text{len} + 1) + 1 + \ldots + \text{len} \\ \equiv\ & \text{start} \times (\text{len} + 1) + (\text{len} \times (\text{len} + 1))/2 \end{aligned}$$

This reasoning assumes that integer overflow cannot occur.

Null pointers

null.c

```
#include <stdio.h>

static void (*action)(void) = NULL;

int main(void) { action(void); }

static void erase_all_files(void) { puts(”deleting all files...”); }
void never_called(void) { action = erase_all_files; }
```

Without optimisation

```
$ clang -o null null.c
$ ./null
Segmentation fault
```

With optimisation

```
$ clang -O3 -o null null.c
$ ./null
deleting all files
```

(Adapted from an example by Krister Walfridsson)

Null pointers: what is going on?

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static void (*action)(void) = NULL;

int main(void) { action(void); }

static void erase_all_files(void) { puts(”deleting all files...”); }
void never_called(void) { action = erase_all_files; }
```

The following reasoning about the program justifies the “optimisation”:

- There is only one assignment to `action`, setting it to `erase_all_files`
- `action` must therefore equal either its initial value (`NULL`) or `erase_all_files`
- if `action` is `NULL`, the program has undefined (unconstrained) behaviour
- so calling `erase_all_files` is valid for all possible values of `action`

Aliasing

alias.c

```c
#include <stdio.h>

long read_write(long *p, int *q) {
  *p = 3;
  *q = 4;
  return *p;
}

int main(void) {
  long x;
  printf("%ld\n", read_write(&x, (int*)&x));
}
```

Without optimisation

```
$ clang -o alias alias.c
$ ./alias
4
```

With optimisation

```
$ clang -O3 -o alias alias.c
$ ./alias
3
```

Aliasing: what is going on?

alias.c (excerpt)

```
long read_write(long *p, int *q) {
  *p = 3;
  *q = 4;
  return *p;
}
```

C forbids writing to the same object through both `long *` and `int *`.

The compiler assumes that writing to `*q` cannot affect the value at `*p`.

Next time: exceptions