Principles of Program Analysis:

A Sampler of Approaches

Transparencies based on Chapter 1 of the book: Flemming Nielson, Hanne Riis Nielson and Chris Hankin: Principles of Program Analysis. Springer Verlag 2005.

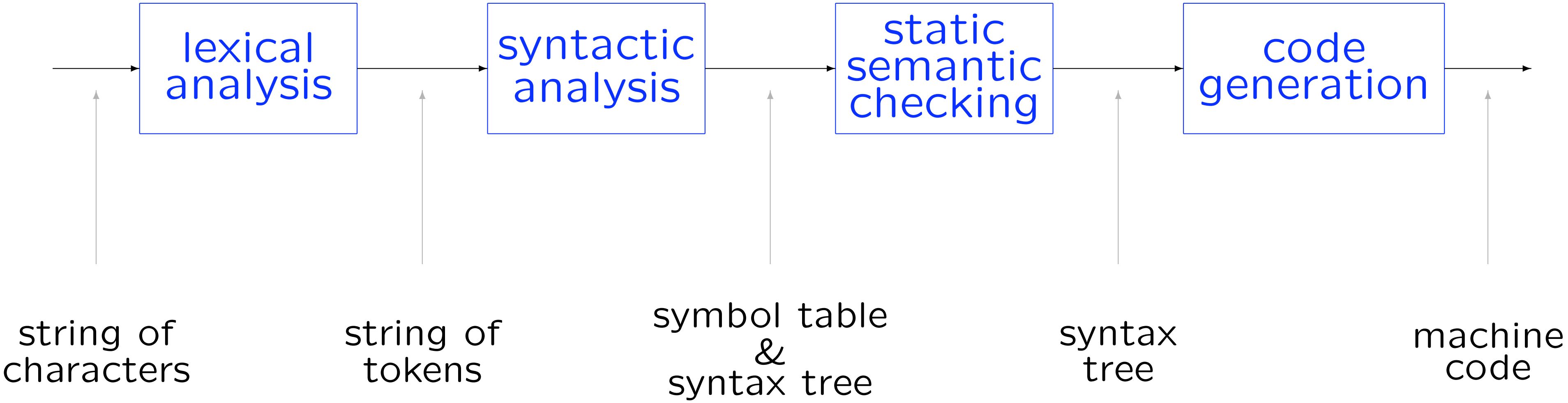
Compiler Optimisation

The classical use of program analysis is to facilitate the construction of compilers generating "optimal" code.

We begin by outlining the structure of optimising compilers.

We then prepare the setting for a worked example where we "optimise" a naive implementation of Algol-like arrays in a C-like language by performing a series of analyses and transformations.

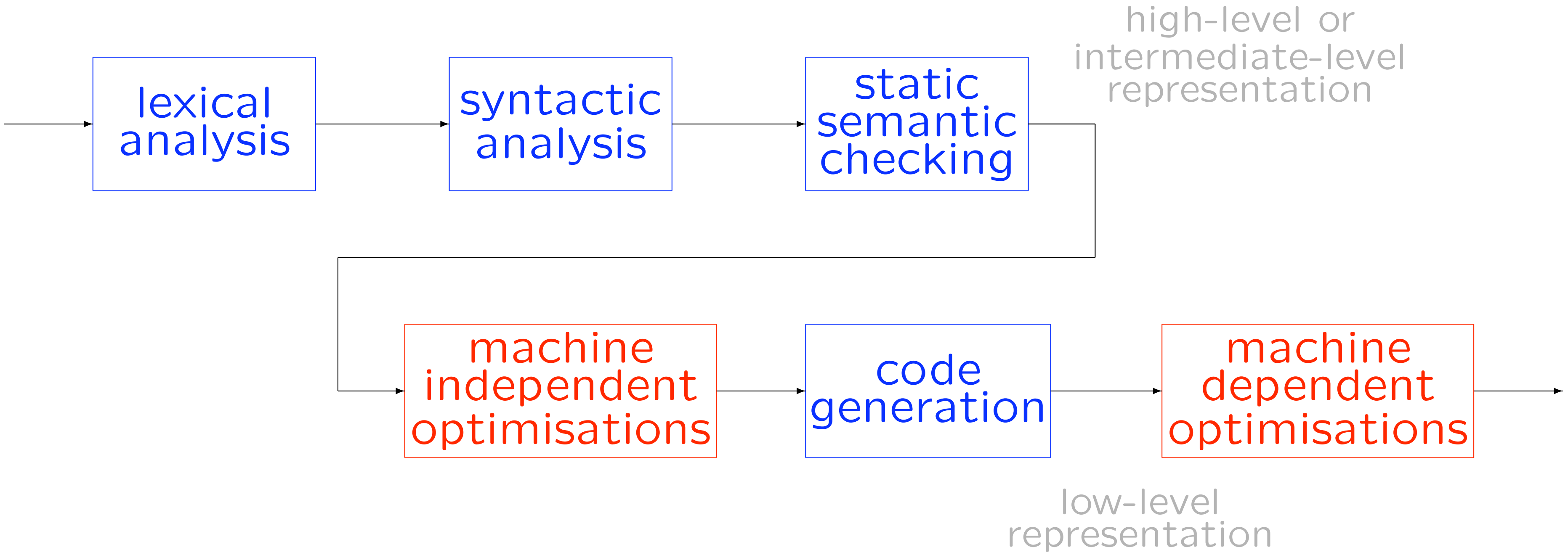
The structure of a simple compiler



Characteristics of a simple compiler:

- many phases – one or more passes
- the compiler is fast – but the code is not very efficient

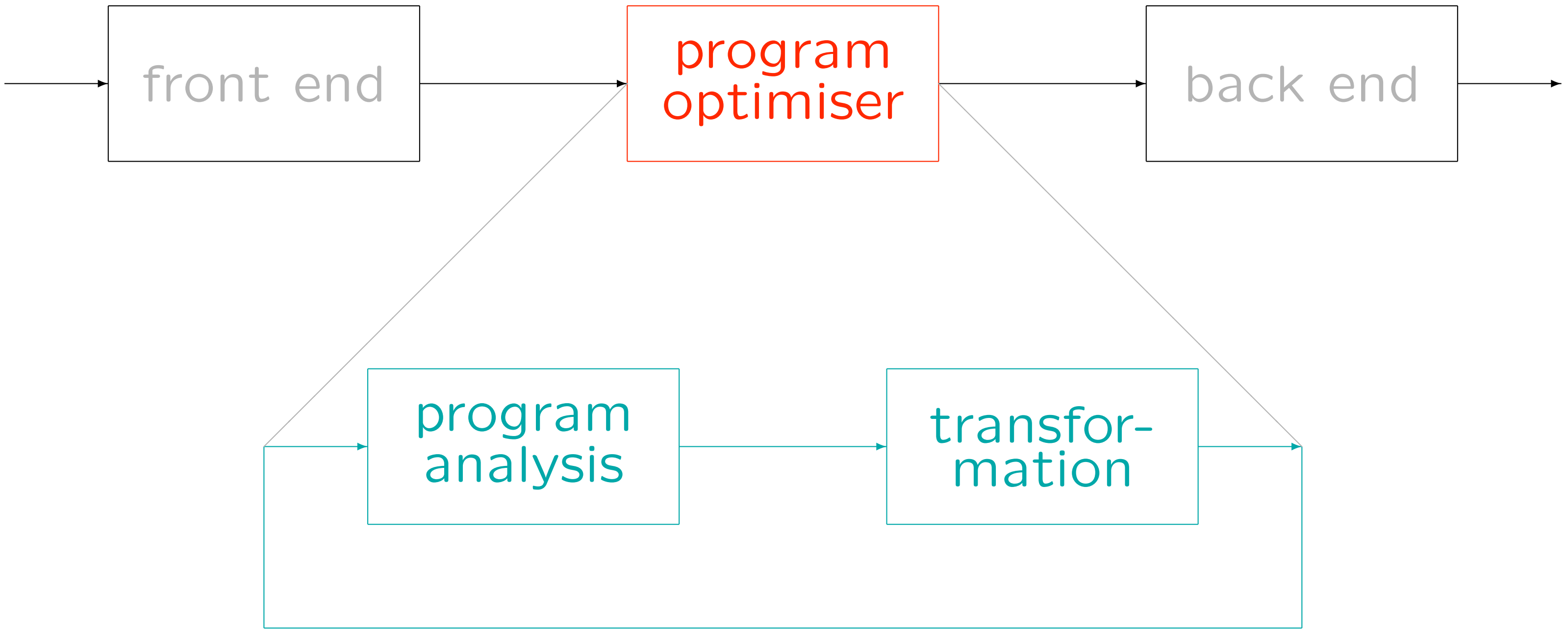
The structure of an optimising compiler



Characteristics of the optimising compiler:

- high-level optimisations: easy to adapt to new architectures
- low-level optimisations: less likely to port to new architectures

The structure of the optimisation phase



front end

program optimiser

back end

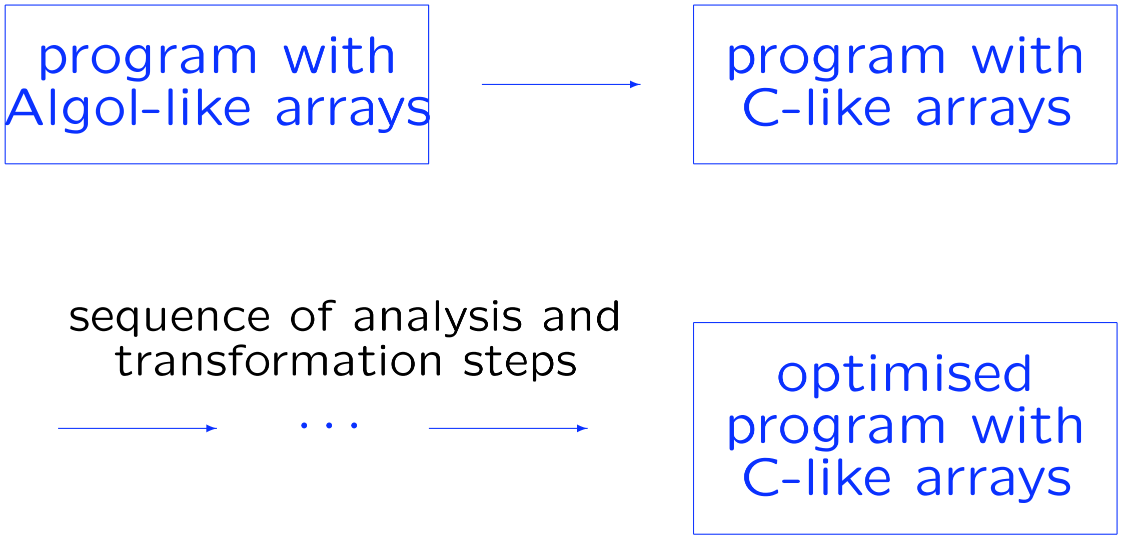
program analysis

transformation

Avoid redundant computations: reuse available results, move loop invariant computations out of loops, ...

Avoid superfluous computations: results known not to be needed, results known already at compile time, ...

Example: Array Optimisation



program with Algol-like arrays

program with C-like arrays

sequence of analysis and transformation steps

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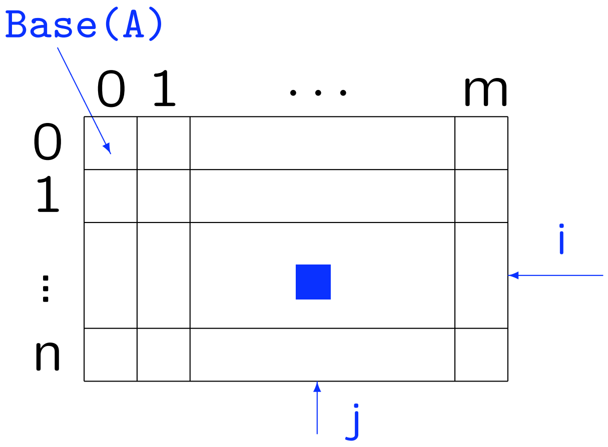
optimised program with C-like arrays

Array representation: Algol vs. C

```
A: array [0:n, 0:m] of integer
```



Accessing the (i,j)'th element of `A`:

in Algol:

```
A[i,j]
```

in C:

```
Cont(Base(A) + i * (m+1) + j)
```

An example program and its naive realisation

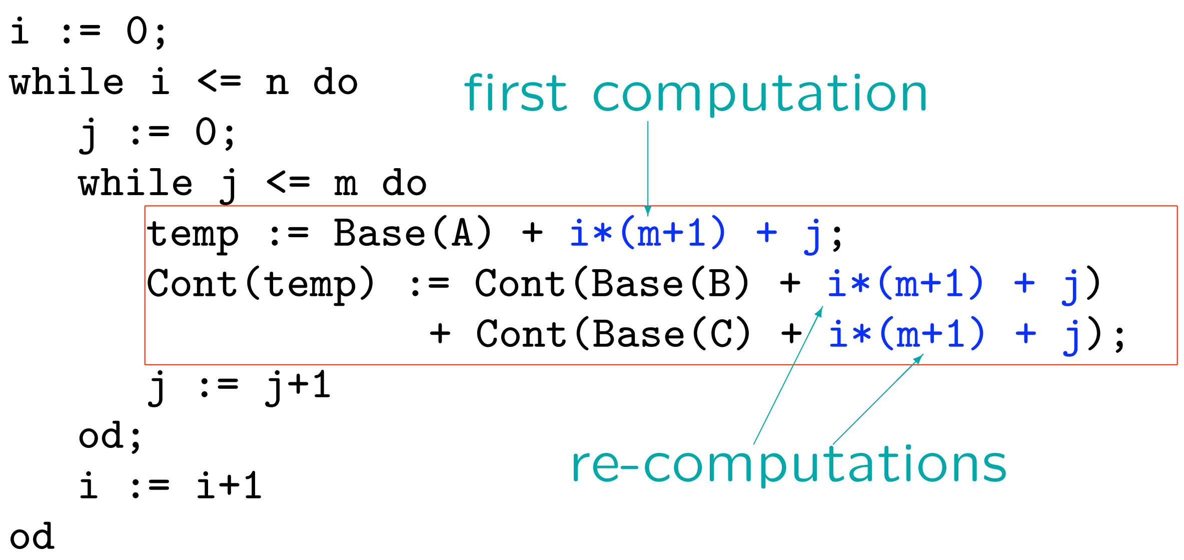
Algol-like arrays:

```
i := 0;
while i <= n do
   j := 0;
   while j <= m do
      A[i,j] := B[i,j] + C[i,j];
      j := j+1
   od;
   i := i+1
od
```

C-like arrays:

```
i := 0;
while i <= n do
   j := 0;
   while j <= m do
      temp := Base(A) + i * (m+1) + j;
      Cont(temp) := Cont(Base(B) + i * (m+1) + j)
                  + Cont(Base(C) + i * (m+1) + j);
      j := j+1
   od;
   i := i+1
od
```

Available Expressions analysis and Common Subexpression Elimination



```
i := 0;
while i <= n do
   j := 0;
   while j <= m do
      temp := Base(A) + i*(m+1) + j;
      Cont(temp) := Cont(Base(B) + i*(m+1) + j)
                  + Cont(Base(C) + i*(m+1) + j);
      j := j+1
   od;
   i := i+1
od
```

first computation

re-computations

```
t1 := i * (m+1) + j;
temp := Base(A) + t1;
Cont(temp) := Cont(Base(B)+t1)
           + Cont(Base(C)+t1);
```

Detection of Loop Invariants and Invariant Code Motion

```
i := 0;
while i <= n do
   j := 0;
   while j <= m do
      t1 := i * (m+1) + j;
      temp := Base(A) + t1;
      Cont(temp) := Cont(Base(B) + t1)
                  + Cont(Base(C) + t1);
      j := j+1
   od;
   i := i+1
od
```

loop invariant

```
t2 := i * (m+1);
while j <= m do
   t1 := t2 + j;
   temp := ...
   Cont(temp) := ...
   j := ...
od
```

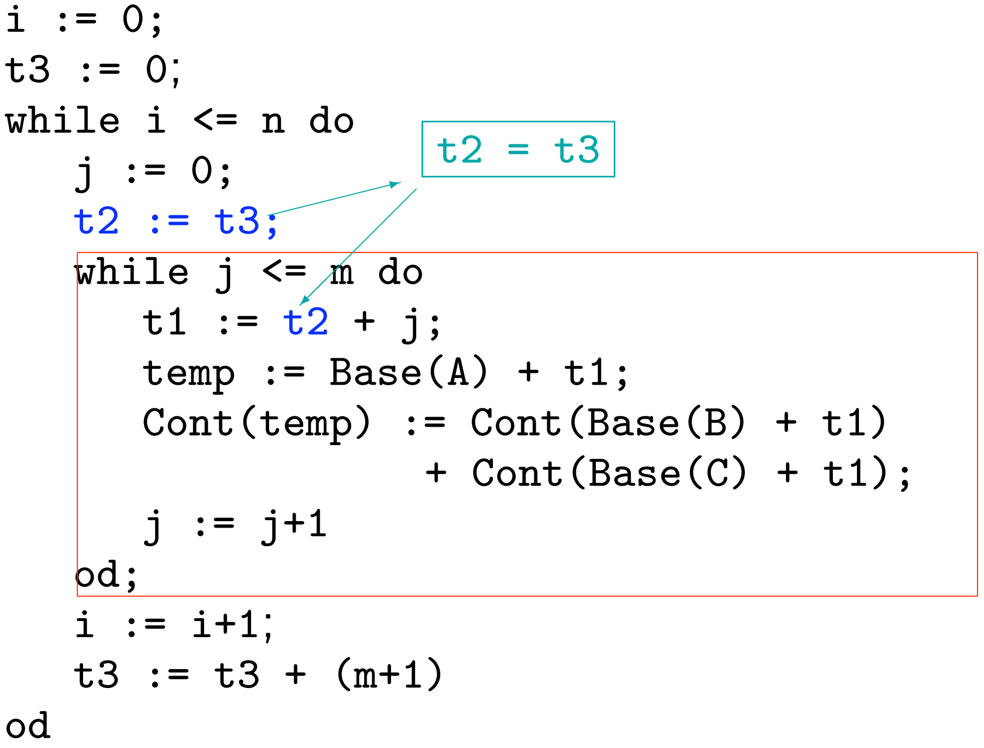
Detection of Induction Variables and Reduction of Strength

```
i := 0;
while i <= n do
   j := 0;
   t2 := i * (m+1);
   while j <= m do
      t1 := t2 + j;
      temp := Base(A) + t1;
      Cont(temp) := Cont(Base(B) + t1)
                  + Cont(Base(C) + t1);
      j := j+1
   od;
   i := i+1
od
```

induction variable

```
i := 0;
t3 := 0;
while i <= n do
   j := 0;
   t2 := t3;
    while j <= m do ...  od
   i := i + 1;
   t3 := t3 + (m+1)
od
```

Equivalent Expressions analysis and Copy Propagation



```
i := 0;
t3 := 0;
while i <= n do
   j := 0;
   t2 := t3;
   while j <= m do
      t1 := t2 + j;
      temp := Base(A) + t1;
      Cont(temp) := Cont(Base(B) + t1)
                  + Cont(Base(C) + t1);
      j := j+1
   od;
   i := i+1;
   t3 := t3 + (m+1)
od
```

```
while j <= m do
   t1 := t3 + j;
   temp := ...;
   Cont(temp) := ...;
   j := ...
od
```

Live Variables analysis and Dead Code Elimination

dead variable

```
i := 0;
t3 := 0;
while i <= n do
   j := 0;
   t2 := t3;
   while j <= m do
      t1 := t3 + j;
      temp := Base(A) + t1;
      Cont(temp) := Cont(Base(B) + t1)
                    + Cont(Base(C) + t1);
      j := j+1
   od;
   i := i+1;
   t3 := t3 + (m+1)
od
```

```
i := 0;
t3 := 0;
while i <= n do
   j := 0;
   while j <= m do
      t1 := t3 + j;
      temp := Base(A) + t1;
      Cont(temp) := Cont(Base(B) + t1)
                    + Cont(Base(C) + t1);
      j := j+1
   od;
   i := i+1;
   t3 := t3 + (m+1)
od
```

Summary of analyses and transformations

Analysis	Transformation
Available expressions analysis	Common subexpression elimination
Detection of loop invariants	Invariant code motion
Detection of induction variables	Strength reduction
Equivalent expression analysis	Copy propagation
Live variables analysis	Dead code elimination

The Essence of Program Analysis

Program analysis offers techniques for predicting
statically at compile-time
safe & efficient approximations
to the set of configurations or behaviours arising
dynamically at run-time

we cannot expect exact answers!

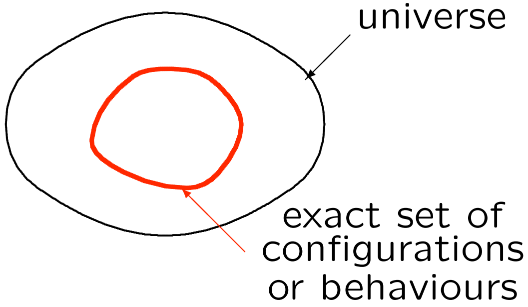
Safe: faithful to the semantics

Efficient: implementation with

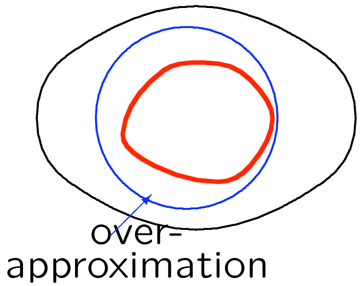
- good time performance and
- low space consumption

The Nature of Approximation

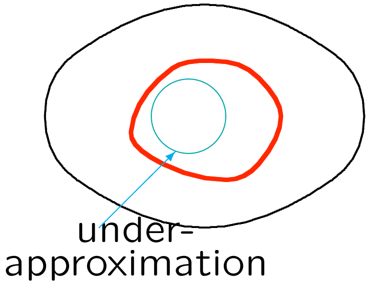
The exact world



Over-approximation



Under-approximation



Slogans: Err on the safe side!
Trade precision for efficiency!