Memory optimisation in a first-order dataflow synchronous language

Cédric Pasteur

PARKAS team, Laboratoire d'Informatique de l'Ecole Normale Supérieure, Paris

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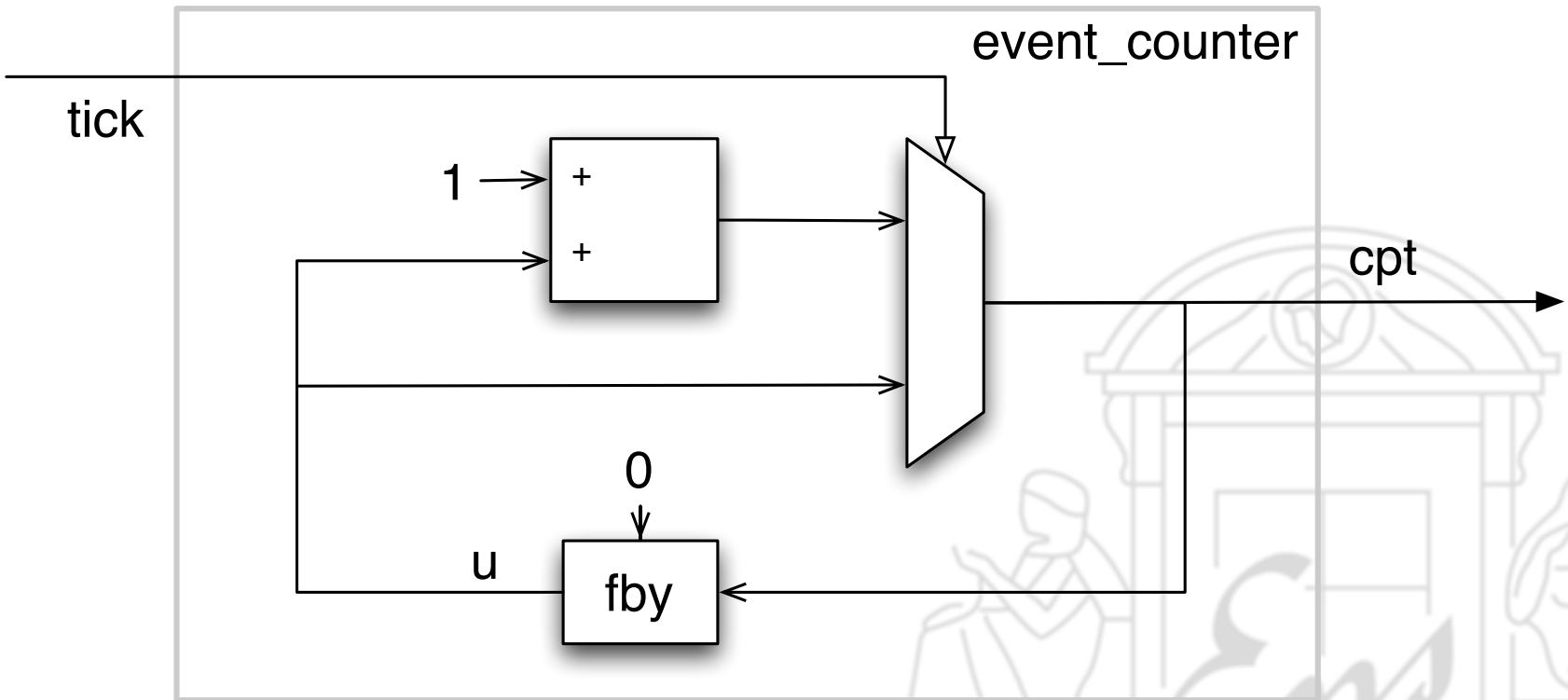
Dataflow synchronous languages

- Academic languages : Lustre, Signal, etc.
- Industrial languages : Scade, LabView, etc.
- Example : a counter

```
node event_counter(tick:bool)
 returns (cpt:int)
var u : int;
let
  u = 0 -> pre cpt;
  cpt = if tick then u + 1 else u;
tel
```

tick	true	false	true	true	...
cpt	1	1	2	3	
pre cpt	nil	1	1	2	
0 -> pre cpt	0	1	1	2	

Visual representation



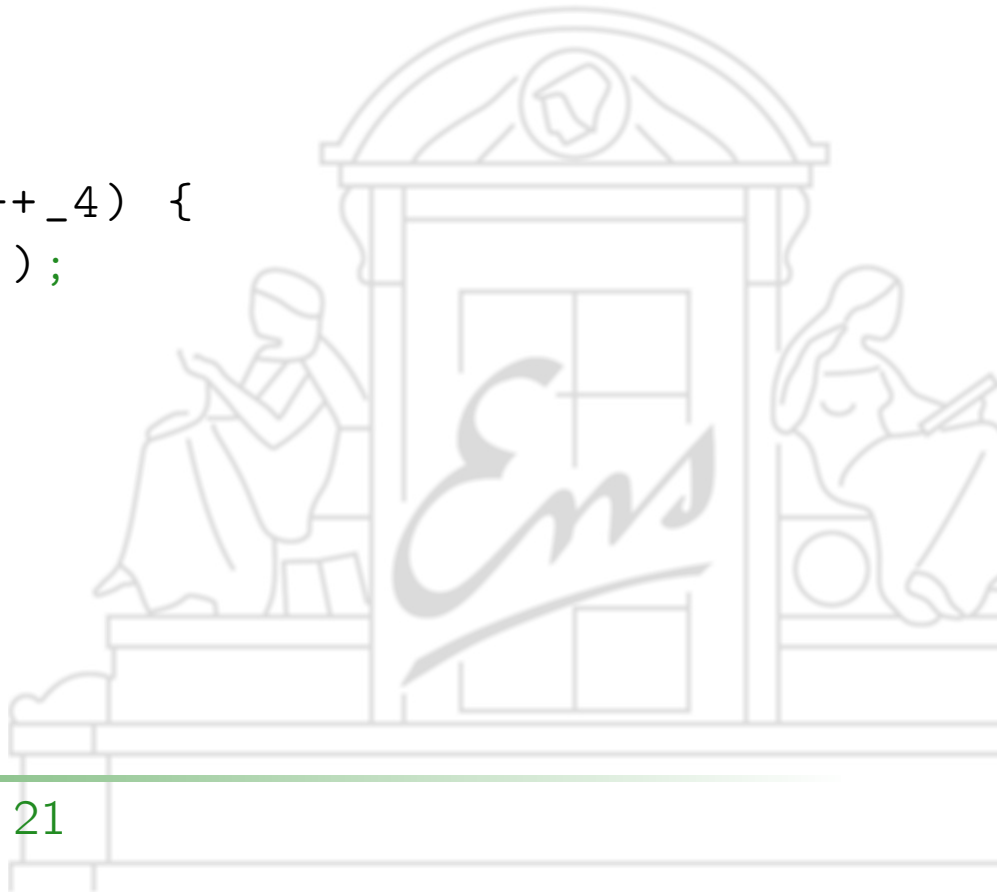
Example : Iterators

The following equations :

```
u = map inc <<n>>(a);
x = mean(u);
```

are compiled to :

```
for (int _4 = 0; _4 < n; ++_4) {
    u[_4] = inc_step(a[_4]);
}
x = mean_step(u);
```



Example : one modification at a time

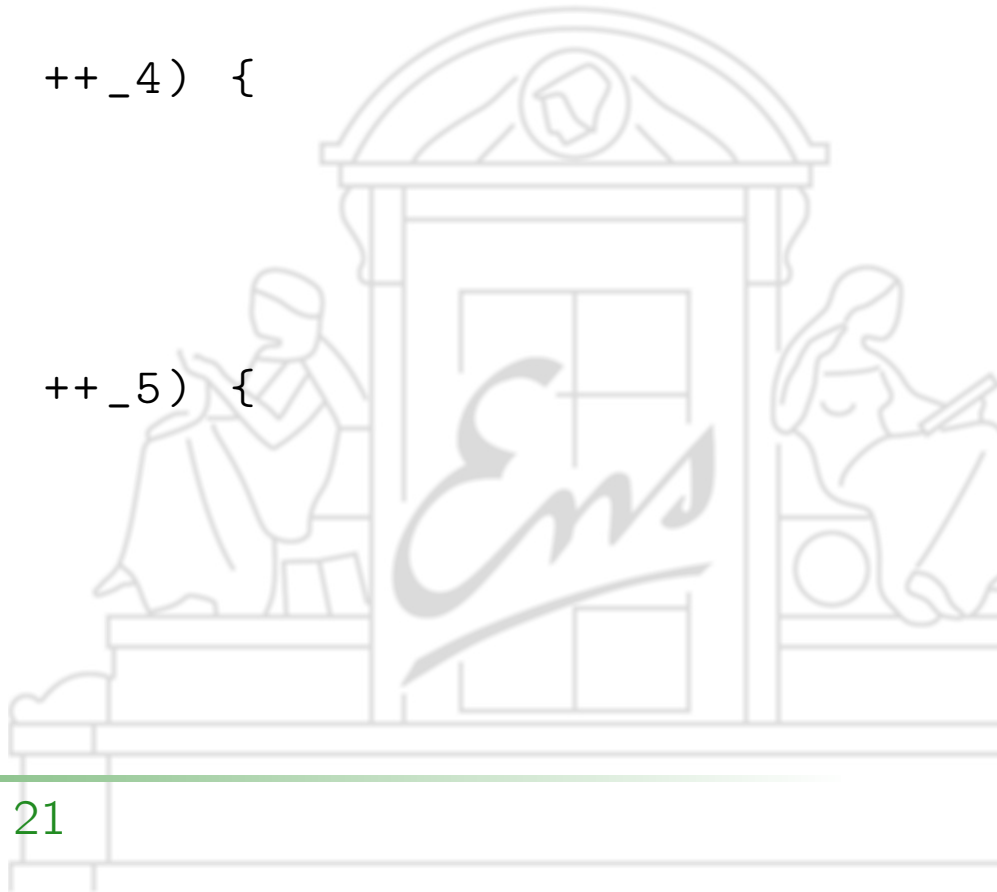
The following equations :

```
u = a with [0] = 0;
v = u with [99] = 0;
```

are compiled to :

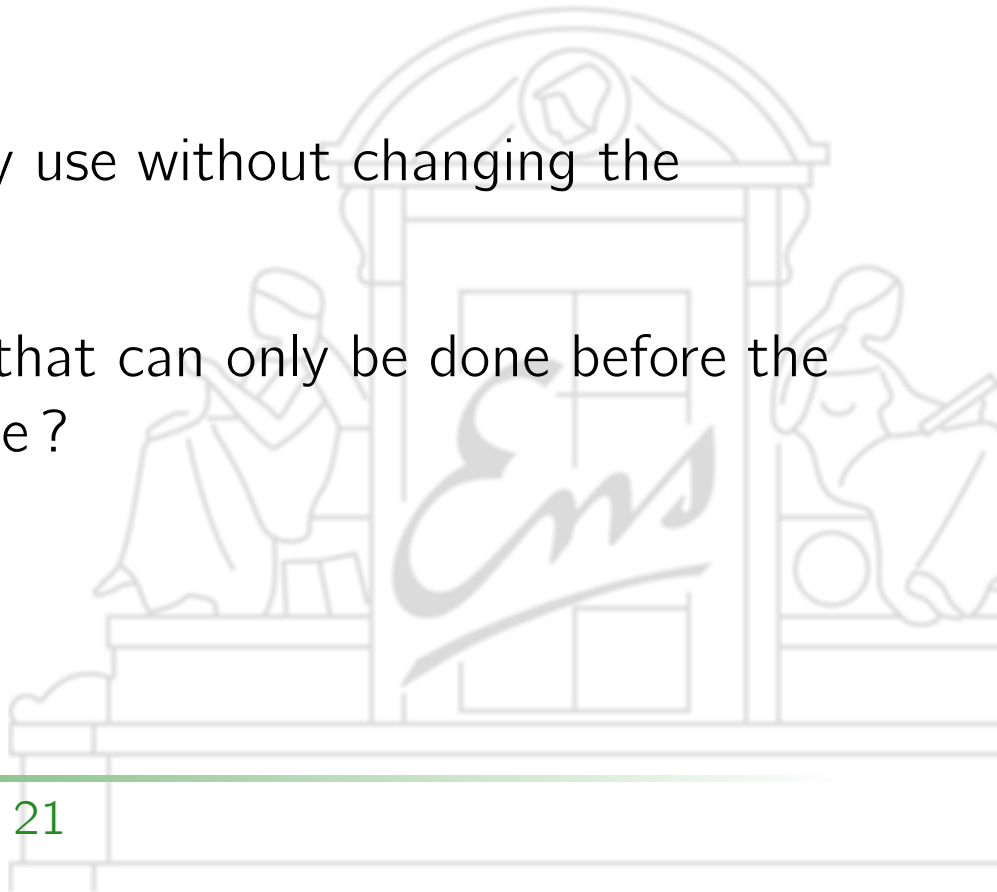
```
for (int _4 = 0; _4 < 100; ++_4) {
    u[_4] = a[_4];
}
u[0] = 0;

for (int _5 = 0; _5 < 100; ++_5) {
    v[_5] = u[_5];
}
v[99] = 0;
```



Eliminating copies

- Problem raised by Esterel Technologies engineers
- Generation of code for safety-critical embedded real-time systems (Scade)
- How do we optimise memory use without changing the language ?
- What are the optimisations that can only be done before the translation to sequential code ?



Traditional solutions

- Problem shared by all functional languages (aka *aggregate update problem* or *update-in-place problem*)
- Static optimisation : deforestation [Gill et al., 1993], operator fusion[Morel, 2005], live range analysis, heuristics [Schnorf et al., 1993],[Abu-Mahmeed et al., 2009]
- Typing : linear or quasilinear types [Wadler, 1990], [Barendsen and Smetsers, 1995], [Kobayashi, 1999]
- Runtime data structures : persistent arrays [Chuang, 1992], garbage collector, reference counting [Scholz, 2003]

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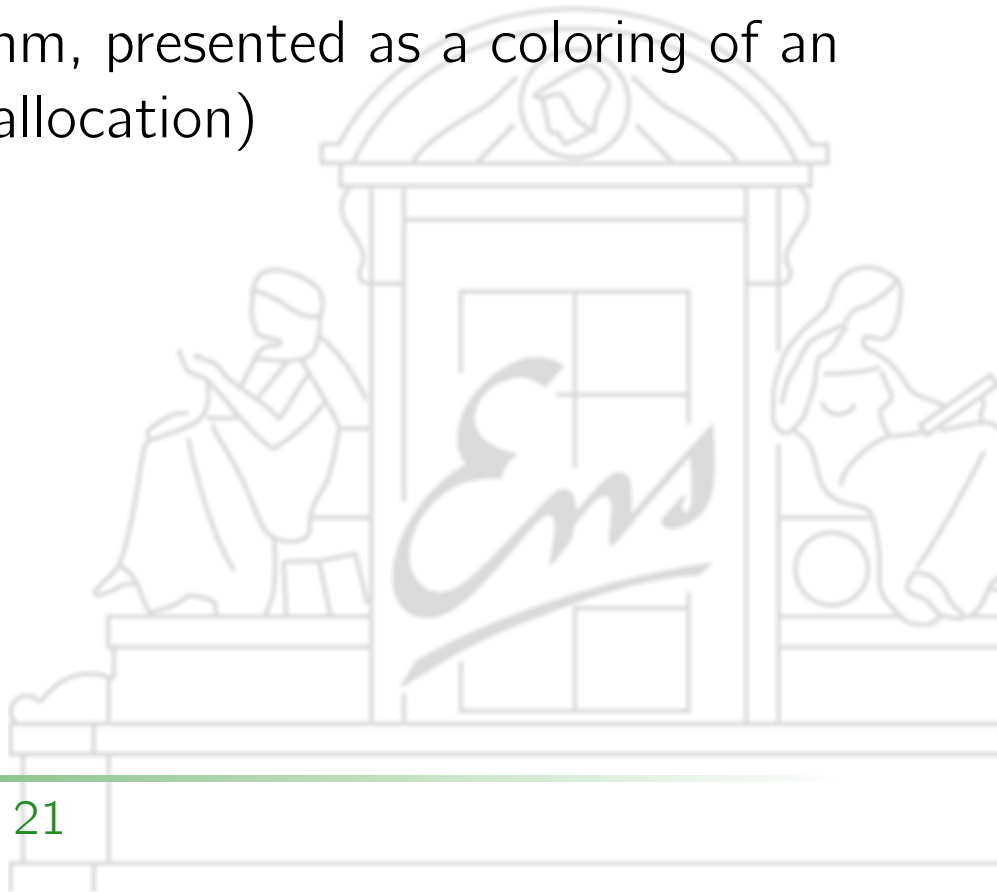
- Runtime data structures : persistent arrays [Chuang, 1992], garbage collector, reference counting [Scholz, 2003]
  $\Rightarrow$ Unusable in real-time systems

Our approach

We combine the first two techniques :

- A static optimisation algorithm, presented as a coloring of an interference graph (register allocation)
- A *semilinear* type system



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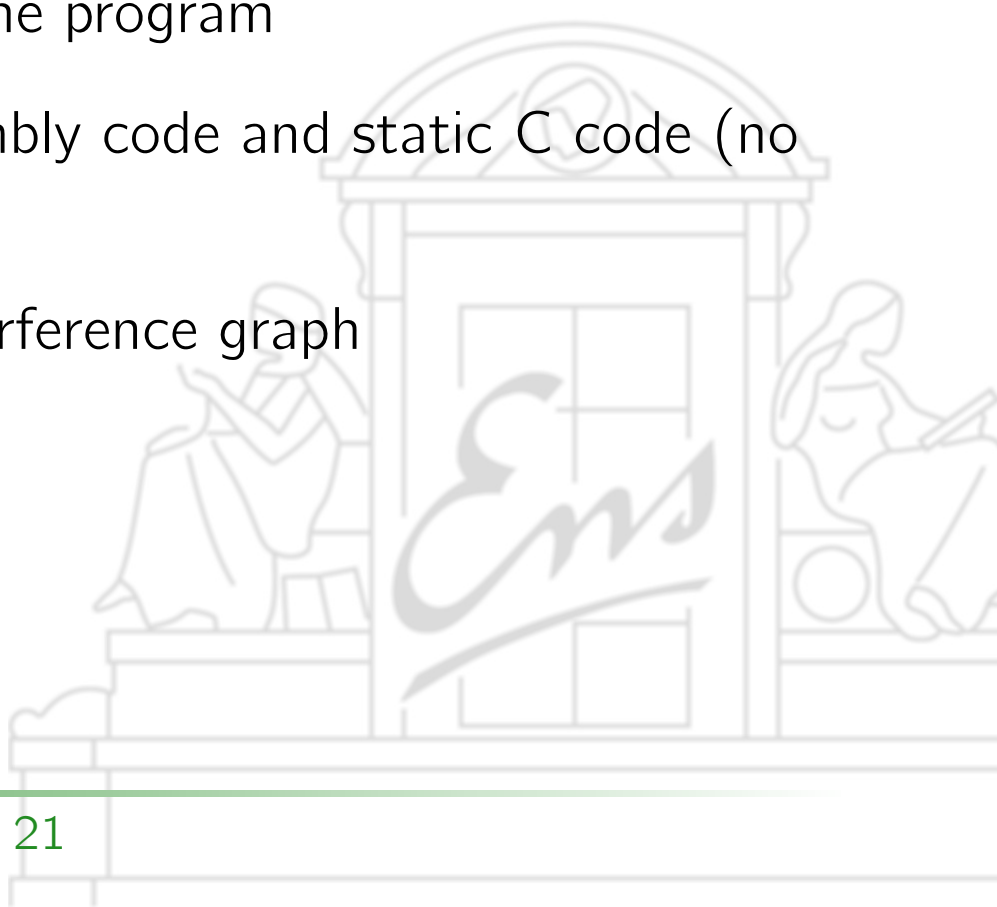
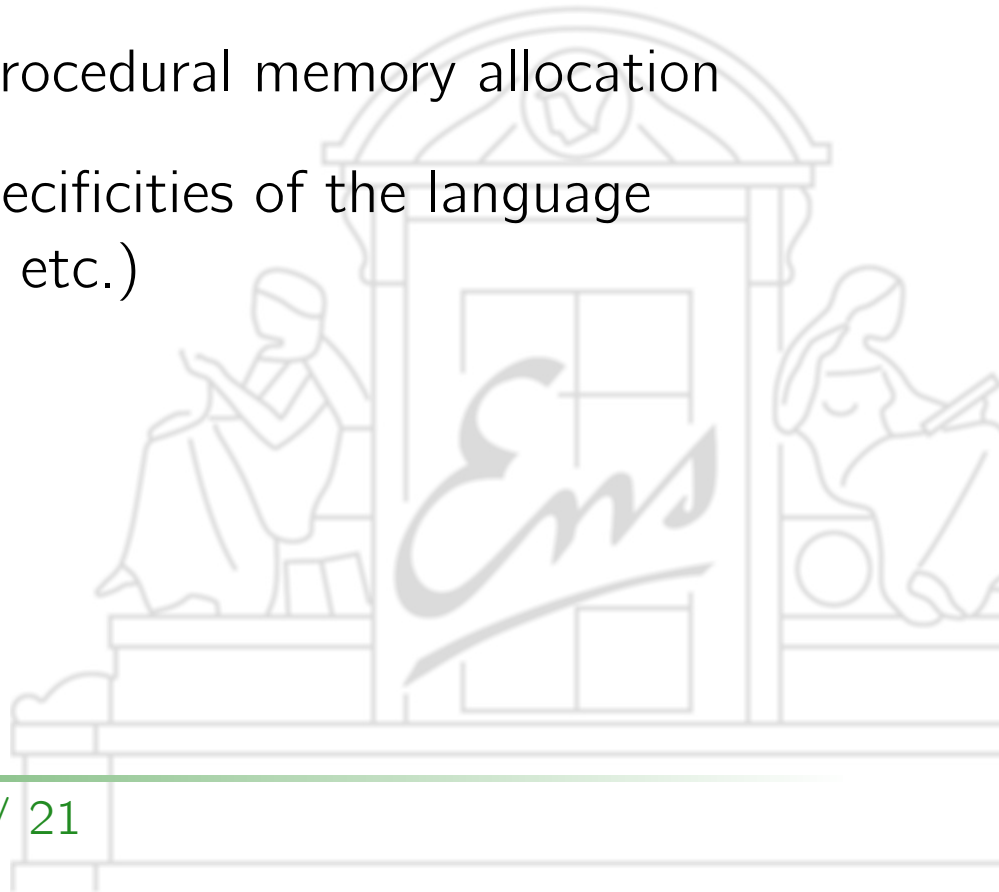
Register allocation and memory optimisation ?

- Same goal : share variables as much as possible without changing the semantics of the program
- Similar constraints for assembly code and static C code (no dynamic memory allocation)
- Method : coloring of an interference graph



Memory allocation

- Definition of interference for a clocked dataflow language
- Calling convention for interprocedural memory allocation
- Algorithm adapted to the specificities of the language (registers, iterators, records, etc.)



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Motivation

The semilinear type system makes the user aware of hidden copies and gives her means to influence the memory allocation algorithm.

Property : No hidden copies

All variables with the same semilinear type correspond to a single memory location.

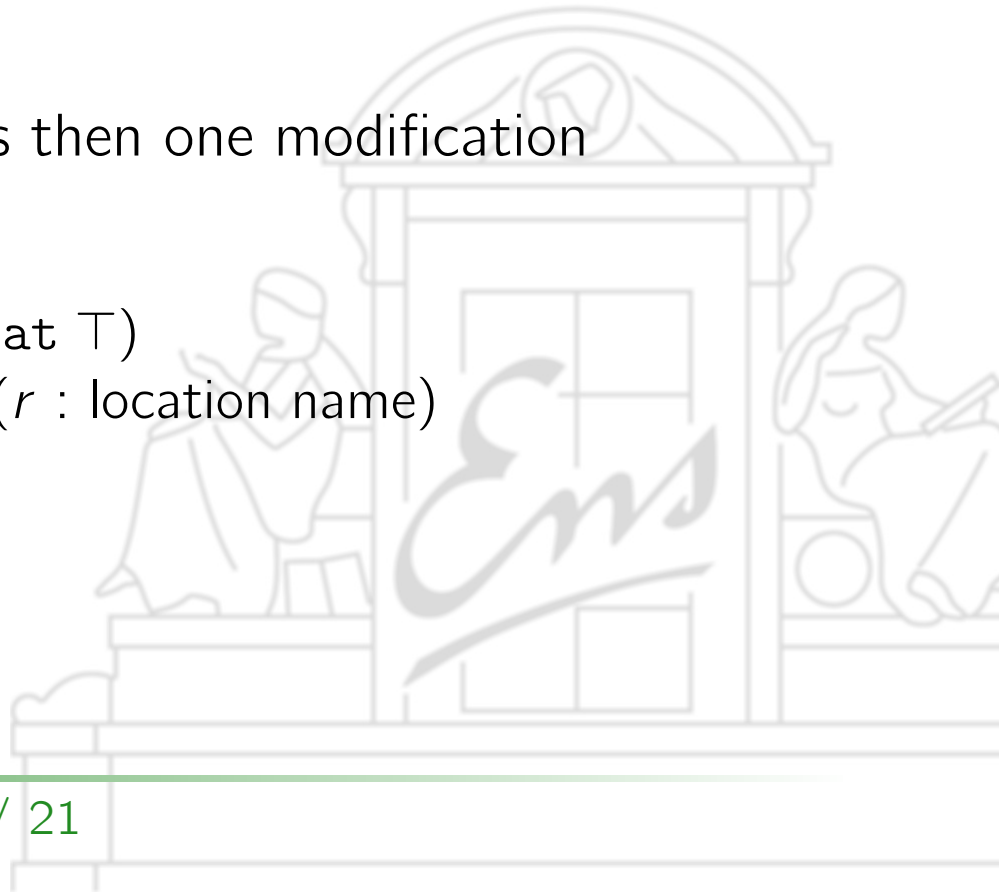
Property : Same semantics

The semantics of a program is the same if we erase all the typing annotations.

Overview

(Linear types [Wadler, 1990], Uniqueness typing
[Barendsen and Smetsers, 1995], Quasi linear types [Kobayashi, 1999])

- Linear type : one use
- *Semilinear* type : many reads then one modification
- Notation :
  - Not linear types : τ (or τ `at` $\top$)
  - *Semilinear* types : τ `at` r (r : location name)



Functions

- *Semilinear* types : many **reads** then one **modification**
- **Read** : function reading a variable
- **Modification** : function modifying (in place) a variable of semilinear type (can be an imported function with side effects)
- Examples :

```
(*read*)
x = t[idx] = select<<idx,n>>(t);
(*modification*)
q = [t with [idx] = v] = update<<n>>(t, idx, v);
```

$$\text{select} : [i, n : \texttt{int}].\ \tau[n] \longrightarrow \tau$$

$$\text{update} : [n : \texttt{int}, r : \texttt{loc}].\ \tau[n]\ \texttt{at}\ r \times \texttt{int} \times \tau \longrightarrow \tau[n]\ \texttt{at}\ r$$

- *Semilinear* type : **many** reads then **one** modification

Var

$$\frac{}{\Delta \mid x : \mu \vdash x : \mu \mid \emptyset}$$

Weakening

$$\frac{\Delta \mid \Gamma \vdash e : \mu' \mid S}{\Delta \mid \Gamma, x : \mu \vdash e : \mu' \mid S}$$

Copy

$$\frac{\Delta \mid \Gamma, x : \tau, x : \tau \vdash e : \mu \mid S}{\Delta \mid \Gamma, x : \tau \vdash e : \mu \mid S}$$

Linear Copy

$$\frac{\Delta \mid \Gamma, x : \tau \ \mathtt{at}\ r, x : \tau \vdash e : \mu \mid S}{\Delta \mid \Gamma, x : \tau \ \mathtt{at}\ r \vdash e : \mu \mid S}$$

Sub

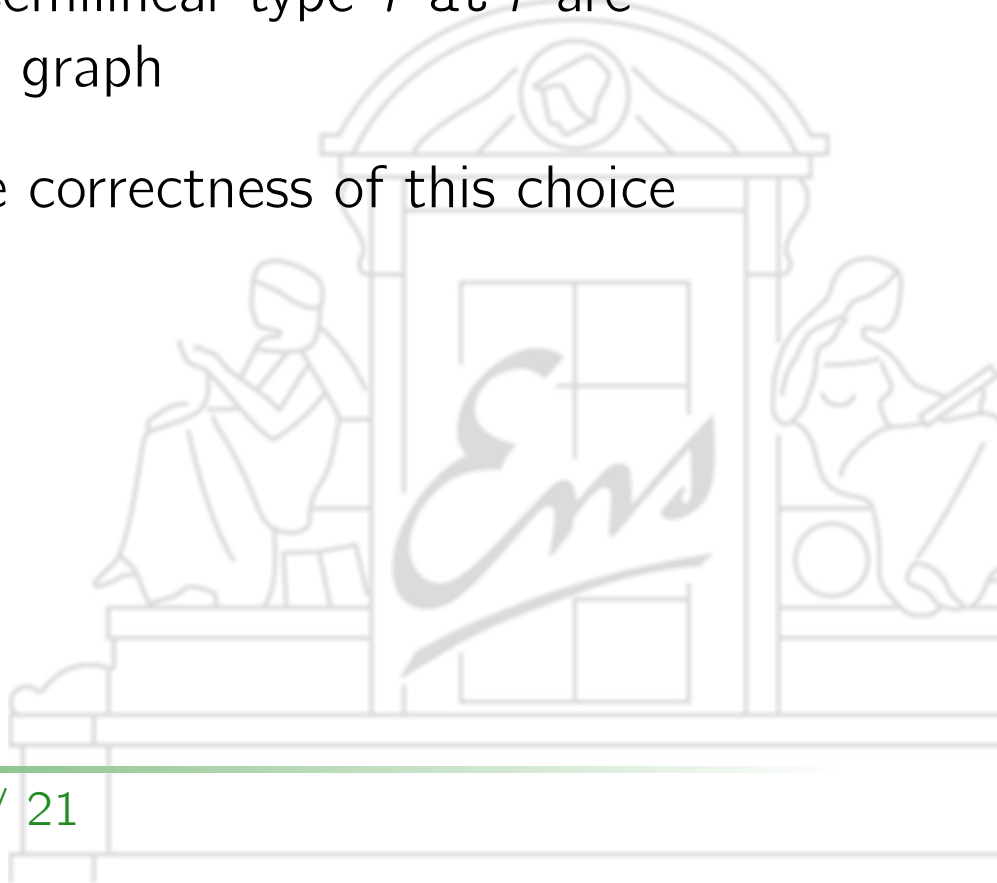
$$\frac{\Delta \mid \Gamma \vdash e : \tau \ \mathtt{at}\ r \mid S}{\Delta \mid \Gamma \vdash e : \tau \mid S}$$

- *Semilinear* types : many reads **then** one modification
- The modification must be done after the reads

```
node (t:int^n at r)
  returns (t2: int^n at r; v:int)
let
  t2 = t with [0] = 0;
  v = t[3] + t2[3];
tel
```

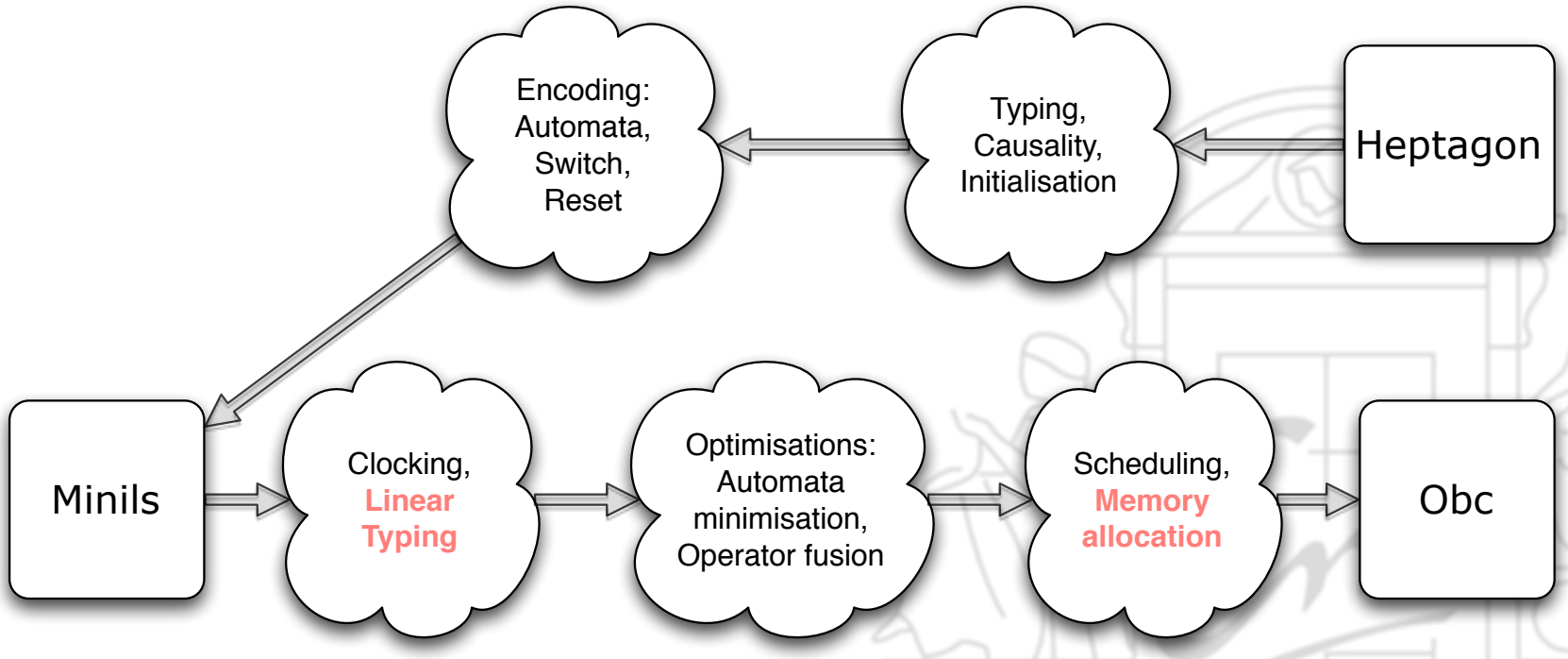
Relation with memory allocation

- All variables with the same semilinear type τ `at` r are coalesced in the interference graph
- The type system ensures the correctness of this choice



Contents

- Functional prototype on the Heptagon language (about 2000 lines of OCaml for typing and memory allocation)



Example : Code generated without optimisation

```
int compute_step(compute_mem* self) {
  int z;
  int x[100];
  int y[100];
  int o[100][100];
  for (int _4 = 0; _4 < 100; ++_4) {
    y[_4] = 0;
  };
  for (int _5 = 0; _5 < 100; ++_5) {
    x[_5] = y[_5];
  };
  for (int i_17 = 0; i_17 < 100; ++i_17) {
    f_step(self->m1[i_17], x, &self->_2[i_17]);
    for (int _6 = 0; _6 < 100; ++_6) {
      o[i_17][_6] = self->_2[i_17].o[_6];
    };
    for (int _7 = 0; _7 < 100; ++_7) {
      x[_7] = self->_2[i_17].acc_out[_7];
    };
  };
  for (int _8 = 0; _8 < 100; ++_8) {
    for (int _9 = 0; _9 < 100; ++_9) {
      self->m1[_8][_9] = o[_8][_9];
    };
  };
  z = o[2][2];
  return z;
}
```

Example : Code generated with optimisation

```
int compute_step(compute_mem* self) {
  int z;
  int r_16[100];
  for (int _4 = 0; _4 < 100; ++_4) {
    r_16[_4] = 0;
  };
  for (int i_25 = 0; i_25 < 100; ++i_25) {
    f_step(self->r_17[i_25], r_16, &self->_2[i_25]);
  };
  z = self->r_17[2][2];
  return z;
}
```

- Half the memory, twice as fast

Why don't we let gcc do it ?

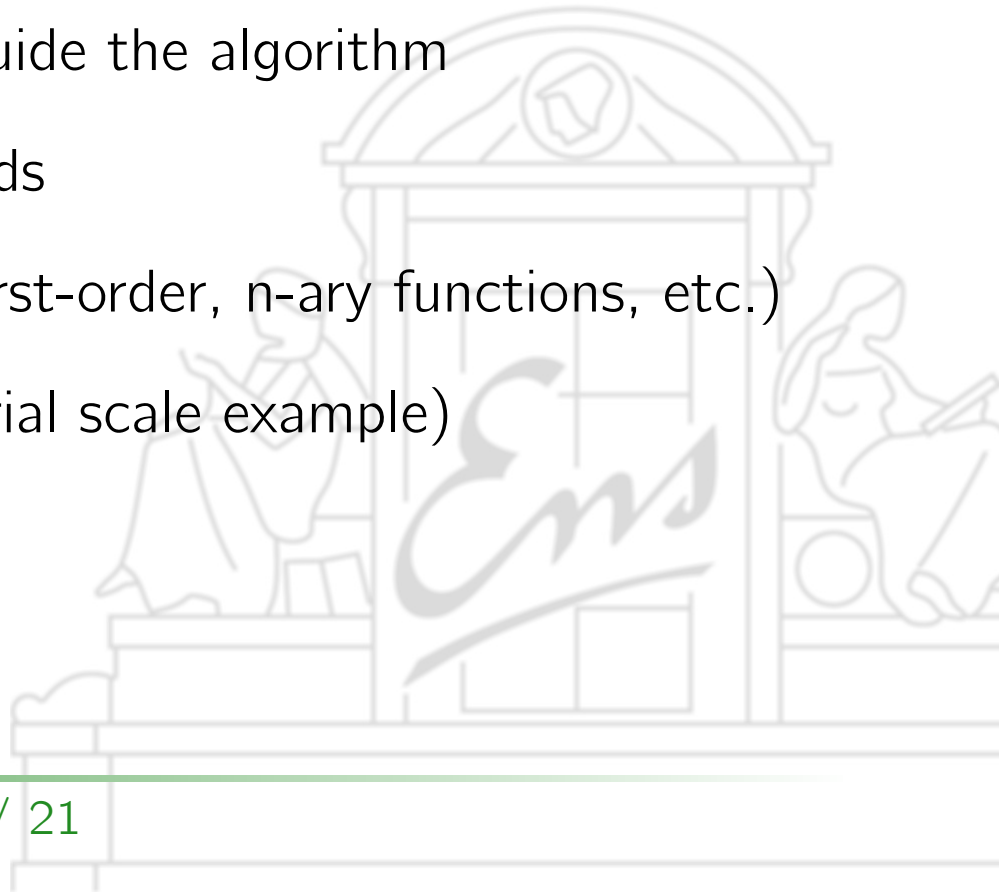
- Compilation hides information
- gcc does *register* allocation, but nothing on arrays
- Stack space is limited (about 8 MB)
- Compilers used for safety-critical systems are not as good as gcc

Table: Result with optimisation with respect to the result without optimisation (percentage)

	Memory	Time
Single threaded computation on an array	25	100
Iteration on a matrix	50	50
Cellular automata	32	0
Only base types (with -O0)	100	105
Only base types (with -O2)	100	160

Conclusion

- A static optimisation algorithm expressed as a coloring of an interference graph
- Semilinear type system to guide the algorithm
- Reuse of traditionnal methods
- Adapted to the language (first-order, n-ary functions, etc.)
- Good results (but no industrial scale example)



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