Automatic Code Generation of Distributed Parallel Tasks

Onzième rencontre de la communauté française de compilation

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Motivation

Scientific Program

Signal Processing

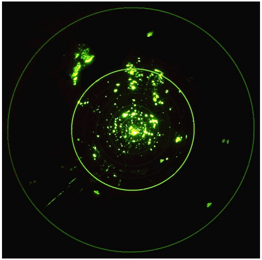
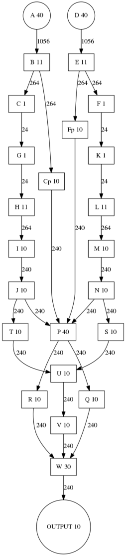


Image Processing



Context

Tools

- Automatic task parallelization (OpenModelica[1])
- Automatic distributed parallelization (Pluto+[2])
- *Black box*

But no automatic distributed parallelization task tool

[1] Mahder Gebremedhin and Peter Fritzson. "Automatic Task Based Analysis and Parallelization in the Context of Equation Based Languages". In: *Proceedings of the 6th International Workshop on Equation-Based Object-Oriented Modeling Languages and Tools*. EOOLT '14. Berlin, Germany: ACM, 2014, pp. 49–52.

[2] Uday Bondhugula. "Compiling Affine Loop Nests for Distributed-memory Parallel Architectures". In: *Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis*. SC '13. Denver, Colorado: ACM, 2013.

Source-to-Source Transformations

- Fortran code
- C code

- *Scientific Program*
- *Image Processing*

- Static analyses
- Instrumentation/ Dynamic analyses
- Transformations
- Source code generation
- Code modelling
- Prettyprint

- Fortran code
- C code

- *Distributed Parallel Code*

Effects and Array Regions

Effects

- Read Effect:
  Set of variables that are read/used by a Statement
- Write Effect:
  Set of variables that are written/defined by a Statement

Convex Array Regions

- Convex Array Region:
  Convex set of elements of an array
- Read Array Region (Read Region):
  Set of convex array regions that are read/used by a Statement
- Write Array Region (Write Region):
  Set of convex array regions that are written/defined by a Statement

Formalization Effects and Array Regions

$$\text{Identifier} \xrightarrow{\rho} \text{Location} \xrightarrow{\sigma} \text{Value}$$

- *Identifier*, *Location*, *Value* `int x = 0;`
- **Environment**, *Env* ρ: *Identifier* $\rightarrow$ *Location*
- **Memory State**, *MemState* σ: *Location* $\rightarrow$ *Value*
- **Statement** S: *Env* $\times$ *MemState* $\rightarrow$ *Env* $\times$ *MemState*
- **Memory Effect** E:
  Statement $\rightarrow$ *Env* $\times$ *MemState* $\rightarrow \mathcal{P}(\textit{Location})$
  - Read Effect E_R
  - Write Effect E_W
- **Array Region** R:
  $\textit{Statement} \rightarrow \textit{Env} \times \textit{MemState} \rightarrow \mathcal{P}((\textit{Location}, \prod_{di \in 0,n} \mathcal{P}(\mathbb{Z}^{di})))$
  - Read Region R_R
  - Write Region R_W

Example Proper Effects and Proper Array Regions

Proper Effects

```
//   Ew: x
x = 0;


//   Ew: i
for(i = 0; i <= 9; i += 1) {
//   Ew: a[i]
//   Er: i
  a[i] = i;
//   Ew: x
//   Er: i x
  x += i;
}


//   Ew: i
for(i = 0; i <= 4; i += 1)
//   Ew: a[i]
//   Er: a[i] i x
  a[i] += x;


//   Ew: i
for(i = 5; i <= 9; i += 1)
//   Ew: a[i]
//   Er: a[i] i x
  a[i] -= x;
```

Proper Array Regions

```
x = 0;


for(i = 0; i <= 9; i += 1) {

//   Rw: (a[PHI1], {PHI1==i, 0<=i, i<=9})
  a[i] = i;


  x += i;
}


for(i = 0; i <= 4; i += 1)
//   Rw: (a[PHI1], {PHI1==i, 0<=i, i<=4})
//   Rr: (a[PHI1], {PHI1==i, 0<=i, i<=4})
  a[i] += x;


for(i = 5; i <= 9; i += 1)
//   Rw: (a[PHI1], {PHI1==i, 5<=i, i<=9})
//   Rr: (a[PHI1], {PHI1==i, 5<=i, i<=9})
  a[i] -= x;
```

Example Cumulated Effects and Array Regions

Cumulated Effects

```
//   Ew: x
x = 0;

//   Ew: a[*] i x
//   Er: i x
for(i = 0; i <= 9; i += 1) {
//   Ew: a[*]
//   Er: i
  a[i] = i;
//   Ew: x
//   Er: i x
  x += i;
}

//   Ew: a[*] i
//   Er: a[*] i x
for(i = 0; i <= 4; i += 1)
//   Ew: a[*]
//   Er: a[*] i x
  a[i] += x;

//   Ew: a[*] i
//   Er: a[*] i x
for(i = 5; i <= 9; i += 1)
//   Ew: a[*]
//   Er: a[*] i x
  a[i] -= x;
```

Array Regions

```
x = 0;


//   Rw: (a[PHI1], {0<=PHI1, PHI1<=9})
for(i = 0; i <= 9; i += 1) {

//   Rw: (a[PHI1], {PHI1==i, 0<=i, i<=9})
  a[i] = i;


  x += i;
}

//   Rw: (a[PHI1], {0<=PHI1, PHI1<=4})
//   Rr: (a[PHI1], {0<=PHI1, PHI1<=4})
for(i = 0; i <= 4; i += 1)
//   Rw: (a[PHI1], {PHI1==i, 0<=i, i<=4})
//   Rr: (a[PHI1], {PHI1==i, 0<=i, i<=4})
  a[i] += x;

//   Rw: (a[PHI1], {5<=PHI1, PHI1<=9})
//   Rr: (a[PHI1], {5<=PHI1, PHI1<=9})
for(i = 5; i <= 9; i += 1)
//   Rw: (a[PHI1], {PHI1==i, 5<=i, i<=9})
//   Rr: (a[PHI1], {PHI1==i, 5<=i, i<=9})
  a[i] -= x;
```

In/Out Effects and Array Regions

Effects

- In Effect:
  Set of variables that are used by a Statement and had to be previously defined
- Out Effect:
  Set of variables that are defined by a Statement and that will be used in its continuation

Array Regions

- In Array Region (In Region):
  Set of convex array regions that are used by a Statement and were previously defined
- Out Array Region (Out Region):
  Set of convex array regions that are defined by a Statement and that will be used in the continuation

Example In/Out Effects and In/Out Array Regions

In/Out Effects

```
//  Eout: x
x = 0;

//  Eout: a[*] x
//  Ein : x
for(i = 0; i <= 9; i += 1) {
//  Eout: a[*]
//  Ein : i
  a[i] = i;
//  Eout: x
//  Ein : i x
  x += i;
}

//  Eout: a[*]
//  Ein : a[*] x
for(i = 0; i <= 4; i += 1)
//  Eout: a[*]
//  Ein : a[*] i x
  a[i] += x;


//  Ein : a[*] x
for(i = 5; i <= 9; i += 1)

//  Ein : a[*] i x
  a[i] -= x;
```

In/Out Array Regions

```

x = 0;


//  Rout: (a[PHI1], {0<=PHI1, PHI1<=9})
for(i = 0; i <= 9; i += 1) {

//  Rout: (a[PHI1], {PHI1==i, 0<=i, i<=9})
  a[i] = i;


  x += i;
}


//  Rin : (a[PHI1], {0<=PHI1, PHI1<=4})
for(i = 0; i <= 4; i += 1)

//  Rin : (a[PHI1], {PHI1==i, 0<=i, i<=4})
  a[i] += x;


//  Rin : (a[PHI1], {5<=PHI1, PHI1<=9})
for(i = 5; i <= 9; i += 1)

//  Rin : (a[PHI1], {PHI1==i, 5<=i, i<=9})
  a[i] -= x;
```

Relation Between Live Variables and In/Out Effects

Live Variables

- Live Variable:
  Set of variables that may be potentially read before their next write
- Live-In: Live Variable immediately before a Statement
- Live-Out: Live Variable immediately after a Statement

Relation Between Live Variables and In/Out Effects

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$$LIVE_{in}(s) = (LIVE_{out}(s) \setminus DEF(s)) \cup USED(s)$$

$$LIVE_{out}(s) = \bigcup_{p \in succ(s)} LIVE_{in}(p)$$

$$LIVE_{out}(f) = \varnothing$$

Relation Between Live Variables and In/Out Effects

Live Variables

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- Live-In: Live Variable immediately before a Statement
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$$LIVE_{in}(s) = (LIVE_{out}(s) \setminus DEF(s)) \cup USED(s)$$

$$LIVE_{out}(s) = \bigcup_{p \in succ(s)} LIVE_{in}(p)$$

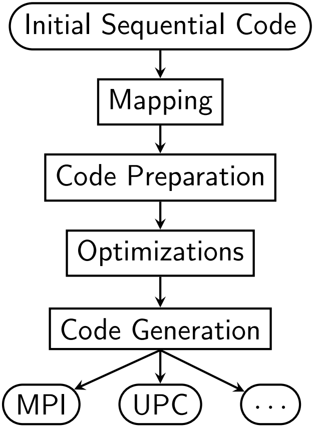
$$LIVE_{out}(f) = \varnothing$$

$$E_{in}(s) = USED(s) \cap LIVE_{in}(s)$$

$$E_{out}(s) = DEF(s) \cap LIVE_{out}(s)$$

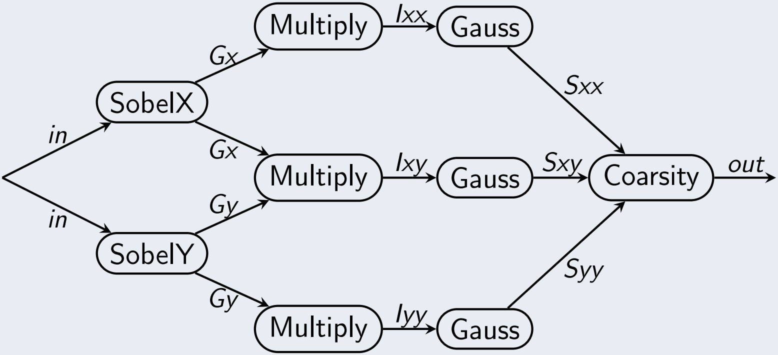
$$LIVE_{out}(s) = [LIVE_{in}(s) \setminus (E_{in}(s) \setminus \ldots)] \cup E_{out}(s)$$

Compilation Process



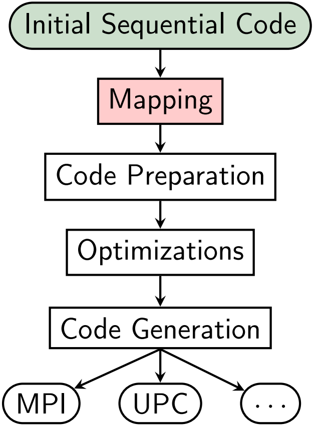
Case Example

Harris&Stephens algorithm[3]



[3] Chris Harris and Mike Stephens. "A combined corner and edge detector". In: *Proc. of Fourth Alvey Vision Conference*. 1988, pp. 147–151

Compilation Process



Mapping

Can be done

- Automatically with a task scheduler[4]
- Manually

Pragma directive

- New pragma `distributed`
- On sequence of instructions, loop, test, etc.
- Not inside loop or condition
- `on_cluster` to define the process to use
- No data dependence information needed [5]

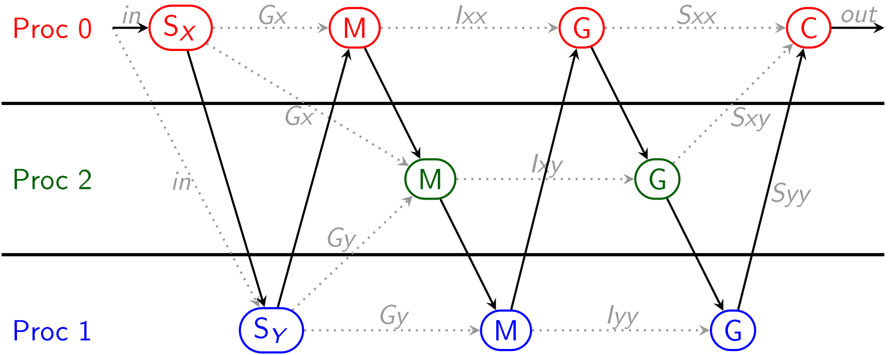
[4] Dounia Khaldi, Pierre Jouvelot, and Corinne Ancourt. "Parallelizing with BDSC, a Resource-constrained Scheduling Algorithm for Shared and Distributed Memory Systems". In: *Parallel Comput.* 41.C (Jan. 2015), pp. 66–89

[5] Martin Tillenius et al. "Resource-Aware Task Scheduling". In: *ACM Trans. Embed. Comput. Syst.* 14.1 (Jan. 2015), 5:1–5:25

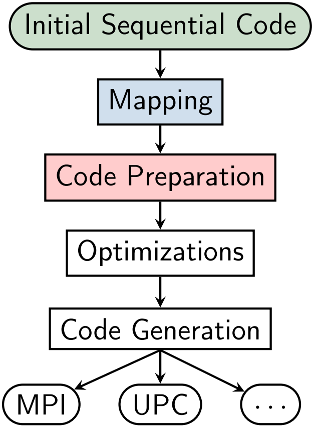
Mapping Example

```
#pragma distributed on_cluster = 0
  init_array(6000, 5900, in);

#pragma distributed on_cluster = 0
  SobelX(6000, 5900, Gx, in);
#pragma distributed on_cluster = 1
  SobelY(6000, 5900, Gy, in);

#pragma distributed on_cluster = 0
  Multiply(6000, 5900, Ixx, Gx, Gx);
#pragma distributed on_cluster = 2
  Multiply(6000, 5900, Ixy, Gx, Gy);
#pragma distributed on_cluster = 1
  Multiply(6000, 5900, Iyy, Gy, Gy);

#pragma distributed on_cluster = 0
  Gauss(6000, 5900, Sxx, Ixx);
#pragma distributed on_cluster = 2
  Gauss(6000, 5900, Sxy, Ixy);
#pragma distributed on_cluster = 1
  Gauss(6000, 5900, Syy, Iyy);

#pragma distributed on_cluster = 0
  CoarsitY(6000, 5900, out, Sxx, Syy, Sxy);

#pragma distributed on_cluster = 0
  print_array(6000, 5900, out);
```

After Mapping



Compilation Process



Code Preparation

Storage Replication

1. **Environment Replication**
   Add declaration for each variable on each process
2. **Store Consistency**
   Add copy/communication for written variables
3. **Localization**
   Substitute "original variables" by "local variables"
4. **Complete Localization**
   Remove "original variables" declarations

Code Preparation – Environment Replication

1. Add declaration for each variable on each process

```
int x;
```

⇒

```
int x;
int x_0;
int x_1;
int x_2;
...
```

Code Preparation – Store Consistency

2. Add copy/communication for written variables

- inside the task
  - More precise
  - Issue for code generation on dynamic cases
  - Redundant copy
- use Write/Out Proper Effects

```
#pragma distributed on_cluster 0
{
  ...
  x=0;
  // copy x on x_0, x_1...
  if (rand()) {
    x=1;
    // copy x on x_0, x_1...
  } else {
    y=1;
    // copy y on y_0, y_1...
  }
  ...
}
```

- between the tasks
  - No dynamic cases
  - No redundant copy
  - Less precise
- use Write/Out Array Regions

```
#pragma distributed on_cluster 0
{
  ...
  x=0;
  if (rand()) {
    x=1;
  } else {
    y=1;
  }
  ...
  // copy x on x_0, x_1...
  // copy y on y_0, y_1...
  ...
}
```

Code Preparation – Localization

3. Substitute “original variables” by “local variables”

```
#pragma distributed on_cluster 0
{
  ...
  x=0;
  ...
  x_0=x;
  x_1=x;
  x_2=x;
  ...
}
```

$\Rightarrow$

```
#pragma distributed on_cluster 0
{
  ...
  x_0=0;
  ...
  x_0=x_0;
  x_1=x_0;
  x_2=x_0;
  ...
}
```

Code Preparation – Localization

3. Substitute "original variables" by "local variables"

```
#pragma distributed on_cluster 0
{
  ...
  x=0;
  ...
  x_0=x;
  x_1=x;
  x_2=x;
  ...
}
```

⇒

```
#pragma distributed on_cluster 0
{
  ...
  x_0=0;
  ...
  x_0=x_0;
  x_1=x_0;
  x_2=x_0;
  ...
}
```

4. Remove "original variables" declarations

```
int x;
int x_0;
int x_1;
int x_2;
...
```

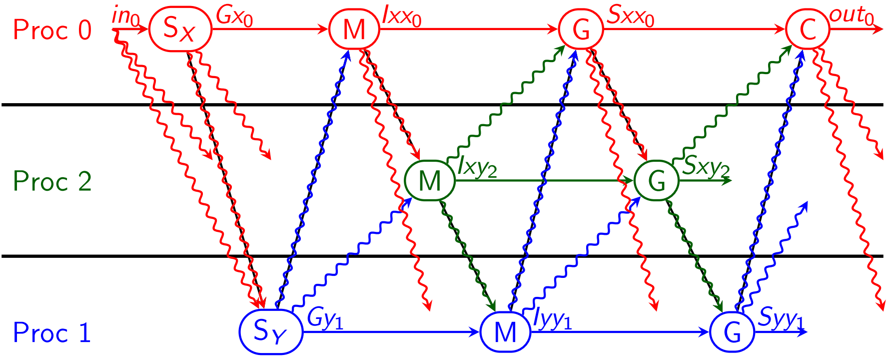
⇒

```
int x_0;
int x_1;
int x_2;
...
```

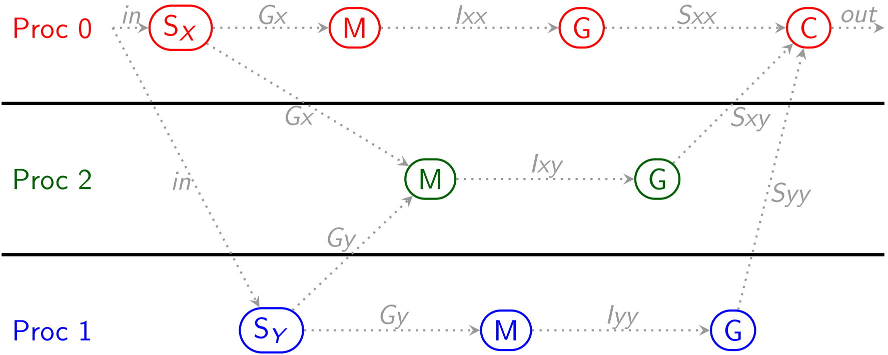
Code Preparation Example

```
/* Variable declaration/allocation. */
double __in_0[6000][5900], __in_1[6000][5900], __in_2[6000][5900];
double __Gx_0[6000][5900], __Gx_1[6000][5900], __Gx_2[6000][5900];
...

#pragma distributed on_cluster = 0
{
  init_array(6000, 5900, __in_0);
  {
    int PHI1, PHI2;
    for (PHI1 = 0; PHI1 <= 5999; PHI1 += 1)
      for (PHI2 = 0; PHI2 <= 5899; PHI2 += 1) {
        __in_1[PHI1][PHI2]=__in_0[PHI1][PHI2];
        __in_2[PHI1][PHI2]=__in_0[PHI1][PHI2];
      }
  }
}

#pragma distributed on_cluster = 0
{
  SobelX(6000, 5900, __Gx_0, __in_0);
  /* Copy __Gx_1=__Gx_0 */
  /* Copy __Gx_2=__Gx_0 */
}
#pragma distributed on_cluster = 1
{
  SobelY(6000, 5900, __Gy_1, __in_1);
  /* Copy __Gy_0=__Gy_1 */
  /* Copy __Gy_2=__Gy_1 */
}

...
```

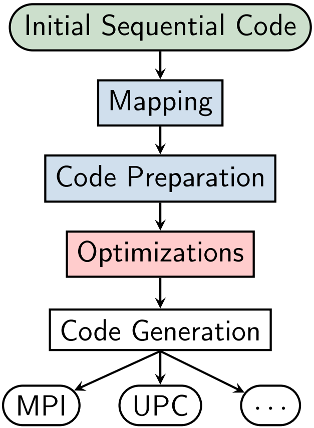
After Code Preparation



Task Graph



Proc 0
in
S_X
Gx
M
Ixx
G
Sxx
C
out
Gx
Sxy
Proc 2
in
M
Ixy
G
Syy
Gy
Proc 1
S_Y
Gy
M
Iyy
G


Initial Sequential Code
Mapping
Code Preparation
Optimizations
Code Generation
MPI
UPC
. . .

Optimizations

Reduce Copy/Communication

- Dead-code Elimination
- Dead-iteration Elimination

Reduce Memory Footprint

- Array Resizing

Reduce Copy/Communication

- Dead-code Elimination
- Dead-iteration Elimination

	case 1	case 2	case 3
task on P	write x_P ~~x_Q = x_P~~ x_R = x_P	write x_P x_Q = x_P ~~x_R = x_P~~	write a_P[0..n] ~~a_Q[0..n]=a_P[0..n]~~ a_Q[0..n/2]=a_P[0..n/2] ~~a_R[0..n]=a_P[0..n]~~ a_R[n/2..n]=a_P[n/2..n]
task on Q Q≠P	...	read x_Q write x_Q x_P = x_Q x_R = x_Q	read a_Q[0..n/2]
task on R R≠{P,Q}	read x_R	read x_R	read a_R[n/2..n]

Reduce Memory Footprint

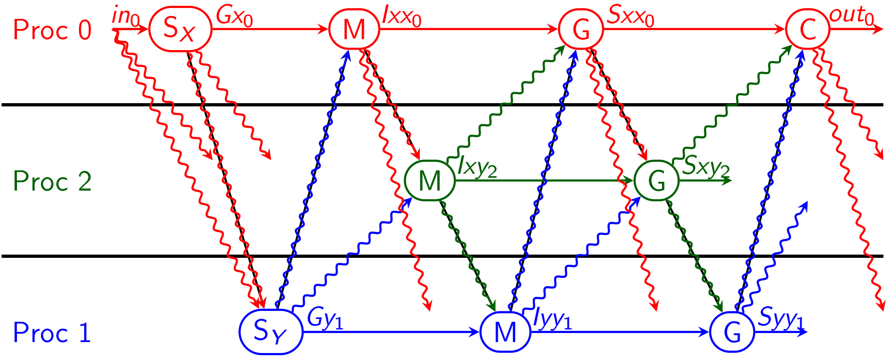
- Array Resizing
  - Use Read/Write Regions
  - Compute new array size
  - Resize array declarations
  - Shift array cell accesses

```c
int a[20];
int i;
for (i=5; i<15; i++)
  a[i] = i*i;
```

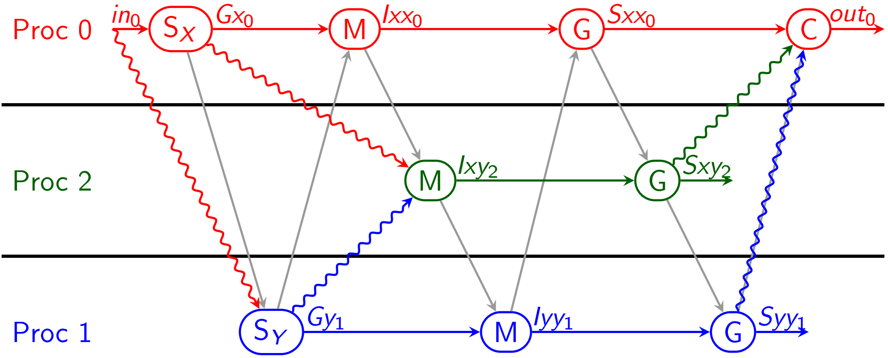
⇒

```c
int a[10];
int i;
for (i=5; i<15; i++)
  a[i-5] = i*i;
```

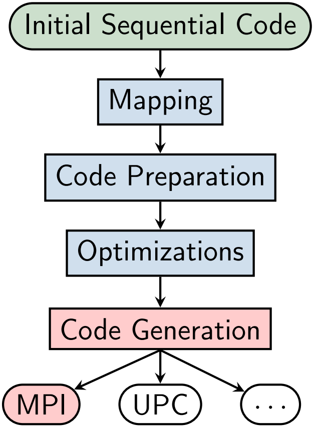
Before Optimizations



After Optimizations



Compilation Process



Parallel Code Generation

MPI Code Generation

- Configure MPI Environment
- Replace pragma block by test on process rank
- Replace copy by
  - Send message for rhs on rhs process to lhs process
  - Receive message for lhs on lhs process from rhs process

MPI Code Generation

- **Configure MPI Environment**
- Replace pragma block by test on process rank
- Replace copy by
  - Send message for rhs on rhs process to lhs process
  - Receive message for lhs on lhs process from rhs process

```
MPI_Status status;
int size, rank;
MPI_Init(&argc, &argv);
MPI_Comm_size(MPI_COMM_WORLD, &size);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
if (size<REQUIRE_PROC_NUMBER) {
  printf("Not␣enough␣processes␣launched!");
  MPI_Finalize();
  return 0;
}
...
MPI_Finalize();
return 0;
```

Parallel Code Generation

MPI Code Generation

- Configure MPI Environment
- **Replace pragma block by test on process rank**
- Replace copy by
  - Send message for rhs on rhs process to lhs process
  - Receive message for lhs on lhs process from rhs process

```
#pragma distributed on_cluster 0
{
  ...
}
```

$\Rightarrow$

```
if (rank==0)
{
  ...
}
```

MPI Code Generation

- Configure MPI Environment
- Replace pragma block by test on process rank
- **Replace copy by**
  - **Send message for rhs on rhs process to lhs process**
  - **Receive message for lhs on lhs process from rhs process**

```
x_1 = x_0;
```

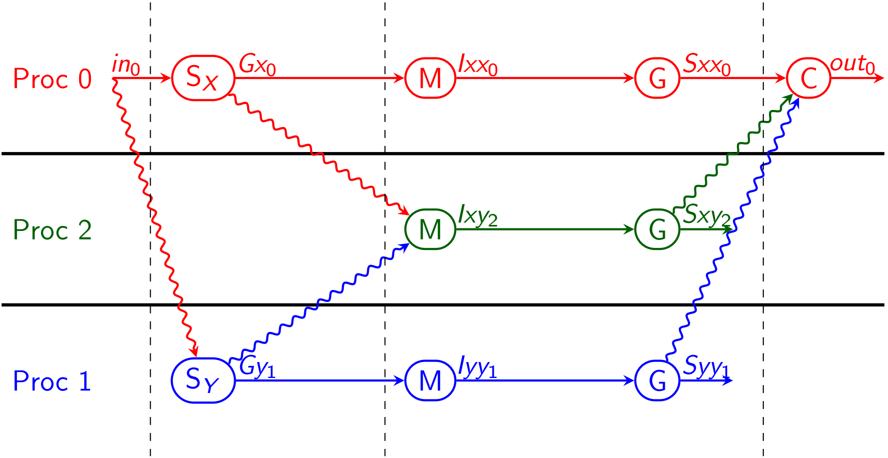
$\Rightarrow$

```
if (rank==0)
  MPI_Send(&x_0, 1, MPI_DOUBLE, 1, 0, MPI_COMM_WORLD);
if (rank==1)
  MPI_Recv(&x_1, 1, MPI_DOUBLE, 0, 0, MPI_COMM_WORLD, &status);
```

Parallel Code Generation Example

```
MPI_Status status;
int size, rank;
MPI_Init(&argc, &argv);
MPI_Comm_size(MPI_COMM_WORLD, &size);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
/* ...Check number of process running... */
/* Variable declaration/allocation. */
double __in_0[6000][5900], __in_1[6000][5900];
...

if (rank == 0) {
  init_array(6000, 5900, __in_0);
  MPI_Send(&__in_0[0][0], 6000 * 5900, MPI_DOUBLE, 1, 0, MPI_COMM_WORLD);
}
if (rank == 1) {
  MPI_Recv(&__in_1[0][0], 6000 * 5900, MPI_DOUBLE, 0, 0, MPI_COMM_WORLD, &status);
}

if (rank == 0) {
  SobelX(6000, 5900, __Gx_0, __in_0);
  MPI_Send(&__Gx_0[0][0], 6000 * 5900, MPI_DOUBLE, 2, 0, MPI_COMM_WORLD);
}
if (rank == 2) {
  MPI_Recv(&__Gx_2[0][0], 6000 * 5900, MPI_DOUBLE, 0, 0, MPI_COMM_WORLD, &status);
}

...

if (rank == 0)
  CoarsityY(6000, 5900, __out_0, __Sxx_0, __Syy_0, __Sxy_0);
if (rank == 0)
  print_array(6000, 5900, __out_0);
MPI_Finalize();
```

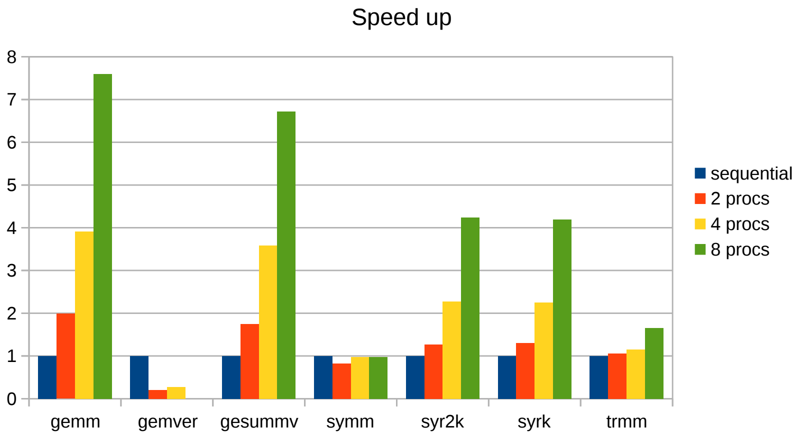
After Parallel Code Generation



Proof Idea

- Initial Sequential Code/Mapping
  Hypothesis: the code is correct
- Code Preparation
  $\forall v, \forall p_1, p_2, \forall T, \forall(\rho', \sigma'), \exists(\rho, \sigma)/(\rho, \sigma) = T(\rho', \sigma'),$
  $\sigma(v_{p_1}) = \sigma(v_{p_2})$
- Optimizations
  $\forall v, \forall p_1, p_2, \forall T_{p_1}, \forall(\rho', \sigma'), \exists(\rho, \sigma)/(\rho, \sigma) = T_{p_1}(\rho', \sigma'),$
  if $\exists T_{p_2} / T_{p_2} \in succ^*(T_{p_1}) \wedge v_{p_2} \in IN(T_{p_2}), \sigma(v_{p_1}) = \sigma(v_{p_2})$
- Parallel Code Generation ($\mathcal{T}$)
  $\forall v, \forall p_1, \sigma_f(v_{p_1}) = \mathcal{T}(\sigma_f)(v_{p_1})$

Experimental Results



Benchmark: BLAS in Polybench
size: ∼3000x4000
type: double

Assumptions & Observations

Assumptions

- Number of processes known at the beginning
- No dynamic parallelism
- Communication overestimation in case of dynamic communications

Observations

- Strongly mapping dependent

Conclusion

Achievement

- Automatic source-to-source transformations
- Succession of simple transformations
- Basic communication functions
- Provable transformations
- Good speed-ups

Future Work

- Improvement of the initial mapping by loop rescheduling
- Comparison with Pluto+
- Asynchronous communications instead of synchronous communications
- Function outlining on each process to improve memory footprint

Automatic Code Generation of Distributed Parallel Tasks

Onzième rencontre de la communauté française de compilation

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