PIPS Is not (just) Polyhedral Software

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Some archeology (I)

- In the 70's vector and parallel machines where the only way to get top performances
- In the 80's automatic vectorization and parallelization became a hot research topic
- 1984: Rémi TRIOLET's PhD @ Mines ParisTech with Paul FEAUTRIER on interprocedural parallelization, convex array regions, polyhedra and linear algebra...
- 1987: François IRIGOIN's PhD @ Mines ParisTech with Paul FEAUTRIER on tiling, control code generation
- 1988: PIPS starts as a project to parallelize scientific applications. Motivation: electrocardiography signal processing code written in Fortran
- 1991: first PIPS PhD: Corinne ANCOURT (on code generation for data communication, under well-known WP65 secret project)

Some archeology (II)

- Followed a lot of internships, PhDs, post-docs, research engineers...
- Use very French specialties
  - Abstract interpretation to « understand » programs (COUSOT, HALBWACHS...)
  - Linear algebra to represent things in a mathematical way (good expressiveness, easy to manipulate) (FOURIER...)
- Automatic vectorization and parallelization: overly high expectations on $\leadsto$ deserted research domains in 90's–00's
- Nowadays parallelism here to prevent processors from melting $\leadsto$ parallel programming is just a way to avoid application to run slower... ☹
- $\leadsto$ Need parallelism for the masses
- Automatic parallelization is one of the ways to go ☺
- Advanced compilation needed anyway

PIPS

- PIPS (Interprocedural Parallelizer of Scientific Programs): Open Source project from Mines ParisTech... 23-year old! ☺
- Funded by many people (French DoD, Industry & Research Departments, University, CEA, IFP, Onera, ANR (French NSF), European projects, regional research clusters...)
- One of the projects that introduced polytope model-based compilation
- $\approx$ 450 KLOC according to David A. Wheeler's `SLOCCount`
- ... but modular and sensible approach to pass through the years
  - $\approx$300 phases (parsers, analyzers, transformations, optimizers, parallelizers, code generators, pretty-printers...) that can be combined for the right purpose
  - Polytope lattice (sparse linear algebra) used for semantics analysis, transformations, cone-based dependance graph, code generation... to deal with big programs, not only loop-nests

PIPS (II)

- Source-to-source to be more independent of targets (trust good work from back-end people ☺)
- NewGen object description language for language-agnostic automatic generation of methods, persistence, object introspection, visitors, accessors, constructors, XML marshaling for interfacing with external tools...
  Cf. presentation @ WIR 2011
- Interprocedural *à la* `make` engine to chain the phases as needed. Lazy construction of resources
- On-going efforts to extend the semantics analysis for C

• Around 15 programmers currently developing in PIPS (Mines ParisTech, HPC Project, IT SudParis, TÉLÉCOM Bretagne) with public `svn`, Trac, `git`, mailing lists, IRC, Plone, Skype... and use it for many projects

Current PIPS usage

- Automatic parallelization (Par4All C & Fortran to OpenMP)
- Distributed memory computing with OpenMP-to-MPI translation [STEP project]
- Generic vectorization for SIMD instructions (SSE, VMX, NEON, CUDA, OpenCL...) (SAC project) [SCALOPES, SMECY]
- Parallelization for embedded systems [SCALOPES, SMECY]
- Compilation for hardware accelerators (Ter@PIX, SPoC, SIMD, FPGA, SCMP, MPPA...) [FREIA, SCALOPES, SIMILAN]
- High-level hardware accelerators synthesis generation for FPGA [PHRASE, CoMap]
- Reverse engineering & decompiler (reconstruction from binary to C)
- Genetic algorithm-based optimization [Luxembourg university+TB]
- Code instrumentation for performance measures
- GPU with CUDA & OpenCL [TransMedi@, FREIA, OpenGPU, MediaGPU, SMECY]

Outline

Vectorization and parallelization

- Historical application for PIPS (1988–)
  - Introduced interprocedural parallelization based on linear algebra method
  - Fortran 77 $\leadsto$ Cray Fortran, CM Fortran, Fortran 90 array syntax, HPF, OpenMP loops
  - Fine grain, corse grain, loop nest...
- Come back with SIMD instruction sets in most recent processors
  - SAC (SIMD Architecture Compiler) in PIPS (2003–2011)
  - Based on unrolling and SLP extraction instead of direct vectorization
  - Generate source with vector types & intrinsic functions for *x*86 SSE/AVX, ARM NEON (smart phones, tablets)...
  - Useful in GPU too: generate OpenCL & CUDA vector data types and intrinsics

Cf. Adrien GUINET's poster @ CGO 2011

Code and memory distribution

- Work Package 65 from European project (1989–1992)
- Transputer-based parallel computer
  - Automatic code parallelization
  - Distribution of sequential code
  - « Compile » a global shared memory with some nodes running computations and some other giving memory services
  - Introduced
    - Code generation by scanning polyhedra
    - Code distribution with a linear algebra method
  - PVM version too
- More recently, generation of SPMD MPI code from OpenMP code by using PIPS convex array regions [STEP @ Institut Télécom SudParis]

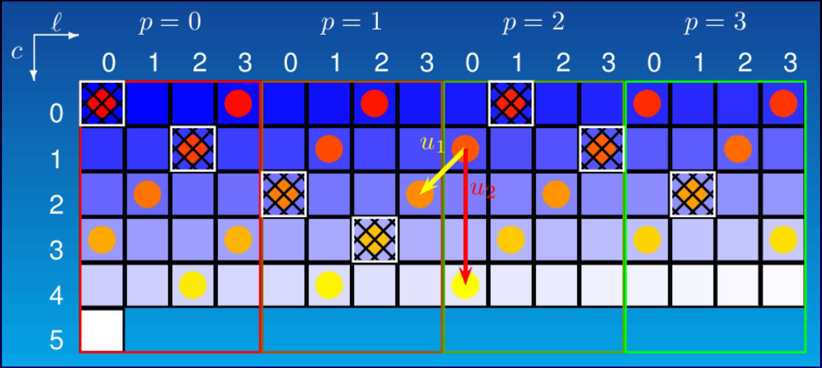
HPF compilation (I)

- Extension of WP65 concepts to HPF compilation (1992–1997)
- HPF = Fortran + Arrays of processors + Affine data-mapping of arrays

`      real A(0:24), B(0:24)` ! $0 \leq a_A \leq 24,\ 0 \leq a_B \leq 24$
`!HPF$ template T(0:80)` ! $0 \leq t \leq 80$
`!HPF$ processors P(0:3)` ! $0 \leq p \leq 3$
`!HPF$ align A(i) with T(3*i)` ! $a_A = 3t$
`!HPF$ align B(i) with A(i)` ! $a_A = a_B$
`!HPF$ distribute T(cyclic(4)) onto P` ! $t = 16c + 4p + \ell$
! $0 \leq \ell < 4$
`      A(0:U:3) = A(0:U:3) + B(1:U+1:3)` ! $i = 3i',\ 0 \leq i \leq$ U
! $a = i$

HPF compilation (II)

- Distribute code and data on processors without shared memory



- Generate allocations, local iterations, optimize communications, remappings and IO

HPF compilation (III)

- Array distribution:

$$
\begin{aligned}
own_{\mathrm{X}}(p) = \{a \mid \exists t, \exists c, \exists \ell :\ & R_{\mathrm{X}} t = A_{\mathrm{X}} a + t_{\mathrm{X}0} \\
& \wedge\ \Pi t = C_{\mathrm{X}} P c + C_{\mathrm{X}} p + \ell_{\mathrm{X}} \wedge\ 0 \leq a < D_{\mathrm{X}} \\
& \wedge\ 0 \leq p < P \wedge\ 0 \leq \ell < C_{\mathrm{X}} \\
& \wedge\ 0 \leq t < T_{\mathrm{X}} \}
\end{aligned}
$$

- Local iterations (*owner compute rule*):

$$compute(p) = \{i \mid S_{\mathrm{X}} i + a_{\mathrm{X}0} \in own_{\mathrm{X}}(p)\}$$

- Elements needed by computation:

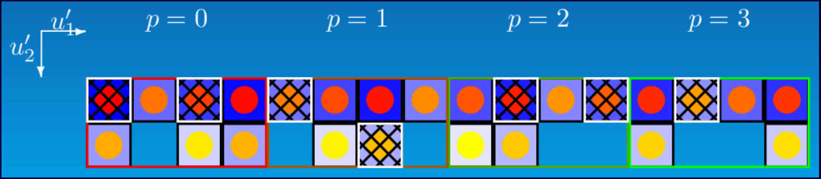
$$view_{\mathrm{Y}}(p) = \{a \mid \exists i \in compute(p) : a = S_{\mathrm{Y}} i + a_{\mathrm{Y}0}\}$$

HPF compilation (IV)

- Send-receive

$$
\begin{aligned}
send_{\Upsilon}(p) &= \{(p', a) \mid a \in own_{\Upsilon}(p) \cap view_{\Upsilon}(p')\} \\
receive_{\Upsilon}(p) &= \{(p', a) \mid a \in view_{\Upsilon}(p) \cap own_{\Upsilon}(p')\}
\end{aligned}
$$

- Compact allocation (HERMITE + non-linear transformation)



- Extension to Phénix machine from ETCA/SEH (work with Pierre FIORINI ⇝ CEO of HPC Project)
- Coming back? Placement directives interesting nowadays to organize manycore data and computations...

Compilation for heterogeneous targets

- Providing high level tools: direct compilation of sequential code
- Adaptation of previous techniques
  - Generate host and accelerator code from pragma annotated code (CoMap) (2004–2007)
  - Generalize and improve for Ter@pix vector accelerator from THALES (2008–2011)
  - Support of CEA SCMP task oriented data-flow machine (2011)
  - Par4All project for GPU and other manycore accelerators (ST Microelectronics P2012, Kalray MPPA...) (2010–)
- Configurations for the SPoC configurable image pipelined processor
  Cf. Fabien COELHO's presentation @ ODES 2011

Program Verification

- Automatic parallelization and abstract interpretation in PIPS: uses verifiers of mathematical polyhedral proofs
- ⇝ Can also be used
  - To extract semantics properties to prove facts about programs
  - Array bound checking and provably redundant array bound checks removing
  - On-going more precise linear integer pre- and post-conditions on programs

Cf. François IRIGOIN presentation @ ACCA 2011

Program synthesis

- Code generation and memory allocation from application descriptions in SPEAR-DE from THALES
- Composition of Simulink, Scade, Xcos/Scicos components by analyzing the C code of components (HPC Project 2010–)

High-level hardware synthesis

- Generate FPGA configurations from sequential code + pragma (2002–2004)
- Use Madeo hardware synthesis tool from UBO, SmallTalk as input language
- Side effect: SmallTalk prettyprinter in PIPS ☺

Decompilation

- Parallelization of binaries?
- Generate raw C-equivalent code with `objdump` + HPC Project crude C translator (2008)
- Apply PIPS code restructurer (control graph restructuring, graph loop recovering...)
- Apply PIPS parallelization

Outline

General organization

- Compiler & tools: `p4a` (Par4All), `sac` (SIMD), `terapyps` (Ter@pix)
- Pass manager: PyPS, `tpips`
- PIPSmake consistency manager
- Phases
  - Passes: inlining, unrolling, communication generation...
  - Analyses: HCFG, DFG, array regions, transformers, preconditions...
  - Prettyprinters: C, Fortran, XML...
- Internal representation
  Cf. Fabien COELHO's presentation @ WIR 2011

Simple memory effects (I)

- Describe memory operations performed by a given statement
- *Proper effects*: memory references local to individual statements
- *Cumulated effects* take into account all effects of compound statements, including those of their sub-statements
- *Summary effects* summarize the cumulated effects for a function and mask effects on local entities

```
//      <may be read >: x[*] y[*]
//      <may be written >: R[*]
//      <   is read >: M N
int corr(int N,float x[N],float y[N],
         int M,float R[M]){
//      <may be read >: x[*] y[*]
//      <may be written >: R[*]
//      <   is read >: M N
 if (M<N) {{
//      <may be read >: N k x[*] y[*]
//      <may be written >: R[*]
//      <   is read >: M
//      <   is written >: k
```

Simple memory effects (II)

```
    for(int k = 0; k <= M-1; k += 1)
//        <may be read >: x[*] y[*]
//        <may be written>: R[*]
//        <  is read >: M N k
     R[k] = corr_body(k,N,&x[k],y);
   }
   return 1;
  }
  else
   return 0;
}
```

Transformers (I)

- Basis for *linear relation analysis* in PIPS
- Represent relation between the store after an instruction and the store before in a linear way (mainly for integer variables)

```
//  T() {}
float corr_body(int k,int N,float x[N],float y[N]){
//  T() {}
 float out = 0.;
//  T(n) {k+n'==N}
 int n = N-k;
//  T(n) {k+n==N,1<=n',n'<=n,1<=n}
 while (n>0) {
//  T(n) {n'==n-1,k+1<=N,0<=n'}
  n = n-1;
//  T() {k+1<=N,0<=n}
  out += x[n]*y[n]/N;
 }
//  T() {k+n<=N,n<=0}
 return out;
}
```

Transformers (II)

Can be used by `forloop_recover` transformation:

```
float corr_body(int k,int N,float x[N],float y[N]){
 float out = 0.;
 int n = N-k;

 for(int n0 = n; n0 >= 1; n0 += -1) {
  n = n0 -1;
  out += x[n]*y[n]/N;
 }
 return out;
}
```

Preconditions (I)

- Affine predicates over scalar variables
- Computed by combination of transformers
- Interprocedural analysis
- Used in many phases (partial evaluation, dead code elimination...)

```
//   P() {k+2<=N,0<=k}
float corr_body(int k,int N,float x[N],float y[N]){
//   P() {k+2<=N,0<=k}
 float out = 0.;
//   P() {k+2<=N,0<=k}
 int n = N-k;
//   P(n) {k+n==N, k+2<=N,0<=k}
 while (n>0) {
//   P(n) {k+2<=N, k+n<=N,0<=k,1<=n}
  n = n-1;
//   P(n) {k+2<=N, k+n+1<=N,0<=k,0<=n}
  out += x[n]*y[n]/N;
 }
//   P(n) {n==0,k+2<=N,0<=k}
```

Preconditions (II)

```
  return out;
}
```

Convex array regions (I)

- Abstract with with affine equalities and inequalities set of array elements accessed by statement
- Many different model of regions: read/write/in (needed)/out (useful after)/...

```
//  <R[PHI1]-W-MAY-{0<=PHI1, PHI1+1<=M,M+1<=N}>
//  <x[PHI1]-R-MAY-{0<=PHI1, PHI1+1<=N,1<=M,M+1<=N}>
//  <y[PHI1]-R-MAY-{0<=PHI1, PHI1+1<=N,1<=M,M+1<=N}>
int corr(int N, float x[N], float y[N],
         int M, float R[M]){
//  <R[PHI1]-W-MAY-{0<=PHI1, PHI1+1<=M,M+1<=N}>
//  <x[PHI1]-R-MAY-{0<=PHI1, PHI1+1<=N,1<=M,M+1<=N}>
//  <y[PHI1]-R-MAY-{0<=PHI1, PHI1+1<=N,1<=M,M+1<=N}>
 if (M<N) {{
//  <R[PHI1]-W-EXACT-{0<=PHI1, PHI1+1<=M,M+1<=N}>
//  <x[PHI1]-R-EXACT-{0<=PHI1, PHI1+1<=N,1<=M,M+1<=N}>
//  <y[PHI1]-R-EXACT-{0<=PHI1, PHI1+1<=N,1<=M,M+1<=N}>
   for(int k = 0; k <= M-1; k += 1)
//  <R[PHI1]-W-EXACT-{PHI1==k,0<=k, k+1<=M,M+1<=N}>
//  <x[PHI1]-R-EXACT-{k<=PHI1, PHI1+1<=N,0<=k, k+1<=M,M+1<=N}>
//  <y[PHI1]-R-EXACT-{0<=PHI1, PHI1+k+1<=N,0<=k, k+1<=M,M+1<=N}>
```

Convex array regions (II)

```
    kernel(M,N,k,R,x,y);
  }
  return 1;
 }
 else
  return 0;
}
```

Linear algebra for analyses and transformations

- PIPS analyses based on the C^3 linear algebra library
- Mainly developed at MINES ParisTech from the 80's
- Integer vectors, matrix, polynomial...
- Mathematical operations, HERMITE's normal form, SMITH's normal form, sorting, simplex...
- $\leadsto$ implementation of all the PIPS polyhedral and linear analyses and transformations (unimodular transformations...)
- In real code, large number of variables including global variables that are mostly not related
  $\leadsto$ Use a sparse representation of constraints: reduce memory storage

Consistency and persistence manager

- Many passes and resources in PIPS...
- Difficult to have always up-to-date informations
- Consistency manager using an *à la* `make` description of dependence relations between resources though passes or analyses
- Lazy construction of resources to produce goal asked by user
- Deal with interprocedural analysis
- A persistance manager allows to stop and resume PIPS later

Pass manager

- PIPS is a source-to-source tool box
- ...but how to use them?
- Simple `tpips` shell like
- New Python-based PyPS
  - Modules, loops and compilation units are exposed as first-class entities
  - Introspection
  - Base of Par4All
    Cf. PIPS tutorial @ CGO 2011

Outline

Computation intensity estimation

- Offloading a loop on accelerator or not?
- Relevant only if the data transfer vs. computational intensity trade-off is interesting
- Execution time estimation given by complexity analysis
- Memory size estimated by region analysis as a polynomial in the program variables

Outlining

- Off-loading to accelerator...
- Use *load work store* idiom
- Extract *work* into new functions to be executed on accelerator
- Use summary effects to build formal parameters
- Use privatization analysis to filter out variables with local use only

Statement Isolation

- Isolate all data accessed by a statement in newly allocated memory areas: simulate the remote memory
- Use *convex array regions* to generate the data copy between the remote and local memories
- DMA can often only transfer efficiently rectangular areas: over-estimate regions using their rectangular hull
- *read regions* are translated into a sequence of host-to-accelerator data transfers
- *written regions* are converted into accelerator-to-host data transfers

Cf. PIPS tutorial @ CGO 2011

Rectangular symbolic tiling and memory footprint

- Array regions estimate memory needed for a computation
- If it exceeds accelerator memory size, cannot run in 1 pass
- Use some tiling, but depends of memory needed
- $\leadsto$ Perform symbolic tiling
- Compute memory footprint according to tiling parameters $\leadsto$ new inequalities
- If not possible to decide at compile time, postpone at run time

From preconditions to iteration clamping *(I)*

- Parallel loop nests are compiled into a CUDA kernel wrapper launch
- The kernel wrapper itself gets its virtual processor index with some `blockIdx.x*blockDim.x + threadIdx.x`
- Since only full blocks of threads are executed, if the number of iterations in a given dimension is not a multiple of the `blockDim`, there are incomplete blocks ☹
- An incomplete block means that some index overrun occurs if all the threads of the block are executed

From preconditions to iteration clamping (II)

- So we need to generate code such as

```
void p4a_kernel_wrapper_0(int k, int l,...)
{
  k = blockIdx.x*blockDim.x + threadIdx.x;
  l = blockIdx.y*blockDim.y + threadIdx.y;
  if (k >= 0 && k <= M - 1 && l >= 0 && l <= M - 1)
    kernel(k, l, ...);
}
```

- Guard ≡ directly translation in C of preconditions on loop indices that are GPU thread indices

```
//  P(i,j,k,l) {0<=k, k<=63, 0<=l, l<=63}
```

Outline

Conclusion (I)

- Manycores & GPU: impressive peak performances and memory bandwidth, power efficient
- Future will be heterogeneous
- ⇝ Programming tools will be heterogeneous too: association of different tools specialized in different domains
- Future challenge: composing tools to make robust compilers
- PIPS uses polyhedral abstractions at high-level with approximations
  - Prefer to deal with whole programs rather than optimal method on small parts (work done in a Mining school, not École Normale Supérieure ☺)
  - Good to prepare work for other more specialized and precise tools
  - On-going interfacing with PoCC in OpenGPU project
- Source-to-source
  - Avoid sticking to much or architectures

Conclusion (II)

- But can also capture architectural details
- Source is a great way to interface $\neq$ tools!

- Extensions in Python with more abstractions and dynamicity
- Basis of Par4All tool to provide end-user tools
- Open Source for community network effect
- More information this afternoon on PIPS and Par4All during the tutorial

Questions?

Historical disclaimer

I'm related to this project for only 19 years, so I ignore many details from the beginning but some colleagues in the audience can answer ☺

Completeness disclaimer

- There are too many things in PIPS and nobody knows about all of them anyway ☺
- Not enough things has been published on PIPS ☹