Machine Learning-Driven Program Transformation to Increase Performance in Heterogeneous Architectures

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Context and Motivation.

Heterogeneous architectures

- Different computing elements.
- Each of them better suited for a type of computation ⇒ high-performance.
- But programming paradigms differ in each component.
- Increased complexity of development, maintenance.
  - More bugs.
  - Less widespread.
- Programming heterogeneous architectures restricted to a few experts.
  - Hinders widespread adoption.

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Scientific code

- Performance is a must.
- Non-trivial algorithms, code very optimized for target architecture.
- Many existing algorithms, implementations.
- Deal with them in a cost-effective, safe way ⇒ mechanize.

Goal.

Develop a framework for sound, semantics-based program transformation of scientific code in order to improve non-functional characteristics.

Transformation example: from $\mathbf{c} = a\mathbf{v} + b\mathbf{v}$ to $\mathbf{c} = (a + b)\mathbf{v}$.

Initial code

```
float c[N], v[N], a, b;
for (int i = 0; i < N; i++)
  c[i] = a * v[i];

for (int i = 0; i < N;i++)
  c[i] += b * v[i];
```

Final code

```
float k = a + b;
for(i = 0; i < N; i++)
   c[i] = k * v[i];
```

Step by Step.

0 - Original

```
float c[N],v[N],a,b;
for(int i=0;i<N;i++)
  c[i] = a*v[i];

for(int i=0;i<N;i++)
  c[i] += b*v[i];
```

1 - For-Loop Fusion

```
for(int i=0;i<N;i++) {
   c[i] = a*v[i];
   c[i] += b*v[i];
}
```

2 - Aug. Addition

```
for(int i=0;i<N;i++) {
   c[i] = a*v[i];
   c[i] = c[i] + b*v[i];
}
```

3 - Join Assignments

```
for(int i=0;i<N;i++)
  c[i] = a*v[i]+b*v[i];
```

4 - Undo Distribute

```
for(int i=0;i<N;i++)
   c[i] = (a+b) * v[i];
```

5 -Inv. Code Motion

```
float k = a + b;
for(int i=0;i<N;i++)
   c[i] = k * v[i];
```

Goal (Cont.).

Capture and respect common properties

Initial code

```
Complex c[N], v[N],  a, b;

for (int i = 0; i < N; i++)
  cmp_mult(v[i], a, c[i]);

Complex aux;

for (int i = 0; i < N;i++) {
  cmp_mult(b, v[i], aux);
  cmp_add(aux, c[i], c[i]);
 }
```

Final code

```
Complex c[N], v[N],  a, b;

Complex k;

cmp_add(a, b, k);

for (int i = 0; i < N;i++)
  cmp_mult(k, v[i], c[i]);
```

Points to Address.

- **Sound.**
  - Respect functional properties.

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    - Different architectures.
    - Different domains.

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- **Targeted.**
    - Improve (certain) non-functional properties (which depend on architecture, aims).

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Use syntactic and **semantic** properties

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Search among applicable rules

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How to. . .

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. . . infer / capture these properties?

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~~Search~~ **Select** applicable rule

. . . identify the right rule(s)?

Rules: Extensible Program Transformations

Example: Undo Distributive Property.

```
for(int i=0;i<N;i++)
  c[i] = a*v[i]+b*v[i];
```

```
for(int i=0;i<N;i++)
   c[i] = (a+b) * v[i];
```

Transformation rule:

```
undo_distributive {
   pattern: {
     (cexpr(e1) * cexpr(e2)) + (cexpr(e1) * cexpr(e3));
   }
   condition: {
     pure(cexpr(e1));
     pure(cexpr(e2));
     pure(cexpr(e3));
   }
   generate: {
     cexpr(e1) * (cexpr(e2) + cexpr(e3));
   }
}
```

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     pure(cexpr(e3));
   }
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   }
}
```

Syntactical pattern

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     pure(cexpr(e2));
     pure(cexpr(e3));
   }
   generate: {
     cexpr(e1) * (cexpr(e2) + cexpr(e3));
   }
}
```

Syntactical pattern

Semantic conditions
(uses predefined properties)

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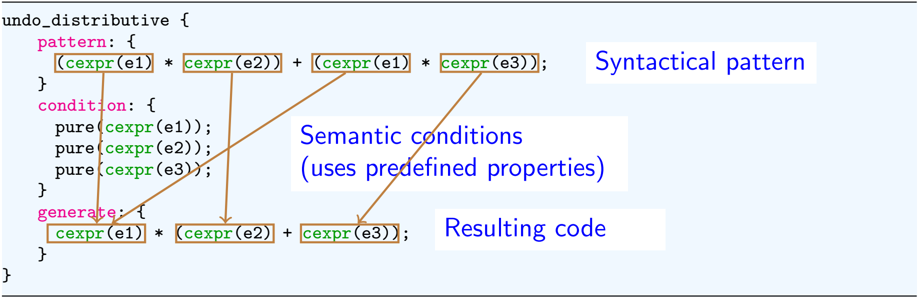


```
undo_distributive {
   pattern: {
    (cexpr(e1) * cexpr(e2)) + (cexpr(e1) * cexpr(e3));
   }
   condition: {
    pure(cexpr(e1));
    pure(cexpr(e2));
    pure(cexpr(e3));
   }
   generate: {
    cexpr(e1) * (cexpr(e2) + cexpr(e3));
   }
}
```

Syntactical pattern

Semantic conditions
(uses predefined properties)

Resulting code

Example: Invariant Code Motion.

```
for(int i=0;i<N;i++)
   c[i] = (a+b) * v[i];
```

```
float k = a + b;
for(int i=0;i<N;i++)
   c[i] = k * v[i];
```

Transformation rule (simplified):

```
loop_inv_code_motion{
   pattern:{
      for (cexpr(ind) = cexpr(ini); cexpr(cond); cexpr(mod)){
         cexpr(e3) = cexpr(e1) * cexpr(e2); }
   }
   condition:{
      pure(cexpr(e2));
      no_reads(cexpr(e2), cexpr(ind));
      no_reads(cexpr(e2), cexpr(e3));
      no_reads_in_written(cexpr(e2), cexpr(mod));
      no_reads_in_written(cexpr(e2), cexpr(e1));
      no_reads_in_written(cexpr(e2), cexpr(e3));
   }
   generate:{
      cdecl(ctype(cexpr(e2)),cexpr(aux));
      cexpr(aux) = cexpr(e2);
      for (cexpr(ind) = cexpr(ini); cexpr(cond); cexpr(mod)){
         cexpr(e3) = cexpr(e1) * cexpr(aux);}
   }
}
```

Syntactical pattern

Semantic conditions (uses predefined properties)

Resulting code

The STML Rule Language.

```
rule_name {
   pattern:  {...}
   condition: {...}
   generate: {...}
}
```

- Inspired by CML [BrownLukKelly 2005], an evolution of CTT [BoekholdKarkowskiCorporaal 1999].
- STML rules expressed in a subset of C.
- Sections:
  - `pattern`:
    - Matches (localizes) code.
    - Meta-expressions (`cexpr`, `cstmt`, ...) substituted by actual symbols before transformation.
  - `condition`:
    - Code properties required by rule (soundness).
  - `generate`: New code, replaces matched section.
  - Not shown: (new) properties of generated code.

STML Constructs.

For all sections

Construct	Description
bin_op(E_{op},E_1,E_2)	represents the binary operation E_1 E_{op} E_2
una_op(E_{op},E)	represents the unary operation E_{op} E

In the condition section

Construct	Description
is_identity(E_{op},E)	E is identity element for E_{op}
no_writes(E_v,(S|[S]|E))	E_v is not written onto in (S|[S]|E)
no_reads(E_v,(S|[S]|E))	E_v is not read from in (S|[S]|E)
no_rw(E_v,(S|[S]|E))	E_v is neither read from nor written onto in (S|[S]|E)
pure((S|[S]|E))	There are no assignments in (S|[S]|E)
is_const(E)	There are variables inside E
is_block(S)	S is a block of statements
is_commutative(E_{op})	Operation E_{op} is commutative
is_associative(E_{op})	Operation E_{op} is associative
not(E_{cond})	E_{cond} is false

STML Constructs (Cont.).

In the generate section

<table>
<tr><th>Construct</th><th>Description</th></tr>
<tr><td>subs((S|[S]|E),$\mathrm{E_f}$,$\mathrm{E_t}$)</td><td>Replace each occurrence of $\mathrm{E_f}$ in (S|[S]|E) for $\mathrm{E_t}$</td></tr>
<tr><td>if_then:{$\mathrm{E_{cond}}$;(S|[S]|E);}</td><td>If $\mathrm{E_{cond}}$ is true, then generate (S|[S]|E)</td></tr>
<tr><td>if_then_else:{$\mathrm{E_{cond}}$; $\mathrm{(S|[S]|E)_t}$;$\mathrm{(S|[S]|E)_e}$;}</td><td>If $\mathrm{E_{cond}}$ is true, then generate $\mathrm{(S|[S]|E)_t}$, else generate $\mathrm{(S|[S]|E)_e}$</td></tr>
<tr><td>gen_list:{[(S|[S]|E)];}</td><td>Each statement/expression in [(S|[S]|E)] produces a different rule consequent</td></tr>
</table>

Extracting Code Properties

Inferring and Expressing Properties.

```
loop_inv_code_motion{
   pattern:{...}
   condition:{
      pure(cexpr(e2));
      no_reads(cexpr(e2), cexpr(ind));
      no_reads(cexpr(e2), cexpr(e3));
      no_reads_in_written(cexpr(e2), cexpr(mod));
      no_reads_in_written(cexpr(e2), cexpr(e1));
      no_reads_in_written(cexpr(e2), cexpr(e3));
   }
   generate:{...}
}
```

1. Which properties are needed?
2. How can we determine whether they hold?

1. Low-level properties, capture characteristics of imperative languages.
   - Destructive assignment & its effects.
   - Aliasing.
   - Memory management
2. Obtained from:
   - Automatic program analysis.
   - User-provided pragmas.

Program Analysis.

- Cetus: source-to-source C compiler written in Java.
- Extensive set of compiler passes working on a high-level IR.
- Analyses and transformations:
  - Dependence analysis.
  - Loop parallelizer.
  - Source program in canonical form.
  - Loop outlining (procedural abstraction of loops).
- Read and Write pragmas (OpenMP and STML — explained later)
- Modifications to Cetus:
  - Generation of STML annotations.
  - Rewriting pass to adapt input code to Cetus (C99).
  - Modified Artistic License $\Longrightarrow$ change Cetus without restrictions.

STML Pragmas.

- Not all properties always automatically inferred.
- `#pragma`s in code.

```
#pragma stml writes c in {0}
for (i = 0; i < N; i++)
  c[i] = i*2;

#pragma stml writes c in {-1,0}
for (i = 1; i < N; i++) {
  c[i-1] = i;
  c[i]   = c[i-1] * 2;
}
```

```
#pragma stml reads c in {-1,0,+1}
for (i = 0; i < N; i++)
  a += c[i-1]+c[i+1]-2*c[i];
```

```
#pragma stml iteration_space 0 N-1
for (i = 0; i < N; i++)
  c[i] = i*2;
```

High-Level Annotations.

- Stemming from POLCA project
- Functional programming flavor.
- Capture algorithmic skeletons:
  - Summarily capture properties of underlying code.
  - Also, can help determine transformation strategies.

```
#pragma polca map F v w

#pragma polca fold F INI v e

#pragma polca itn F INI n w

#pragma polca zipWith F u v w

#pragma polca scanl F INI v w
```

```
#pragma polca map B v c
for(int i=0;i<N;i++)
#pragma polca def B
#pragma polca input v[i]
#pragma polca output c[i]
   c[i] = a*v[i];
```

Information from Annotations.

What map tells us

```
#pragma polca map B v c
for(int i=0;i<N;i++)
#pragma polca def B
#pragma polca input v[i]
#pragma polca output c[i]
   c[i] = a*v[i];
```

- `v` is input to `map`, `c` is output.
- For every `v[i]`, `c[i]` is produced using only `v[i]`.
  - No global variables, no dependencies across iterations.
- Computation of `c[i]` enclosed inside `B`.

⇒ Pragma as summary of simpler properties.

⇒ These are dealt with by rules in program transformation tool.

Translating High-level Annotations to STML.

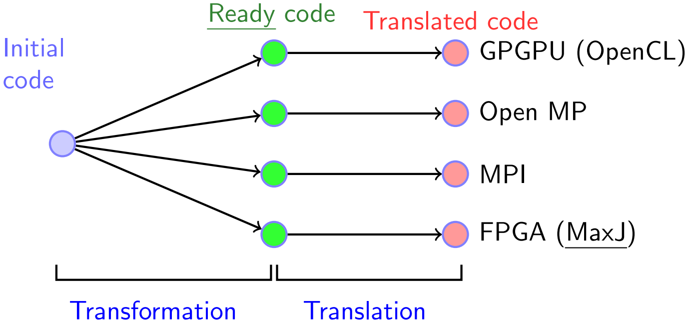
STML properties can be inferred for high-level annotations.

```
#pragma polca map B v c
for(int i=0;i<N;i++)
#pragma polca def B
#pragma polca input v[i]
#pragma polca output c[i]
   c[i] = a*v[i];
```

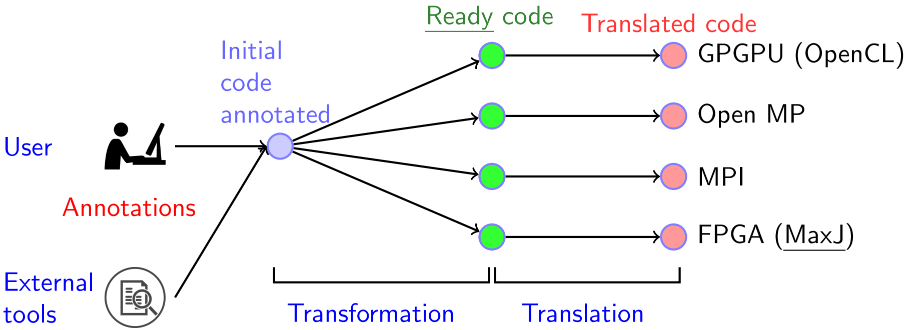
→

```
#pragma stml reads v in {0}
#pragma stml writes c in {0}
#pragma stml same_length v c
#pragma stml pure B
#pragma stml iteration_space 0 length(v)
#pragma stml iteration_independent
for(int i = 0; i < N; i++)
#pragma polca def B
#pragma polca input v[i]
#pragma polca output c[i]
   c[i] = a*v[i];
```

Components of the Transformation Tool.



Components of the Transformation Tool.



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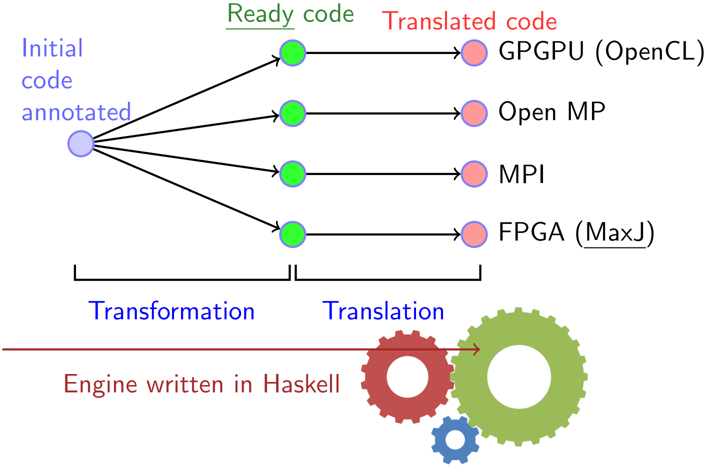

Ready code

Translated code

Initial code annotated

GPGPU (OpenCL)

Open MP

MPI

FPGA (MaxJ)

Transformation

Translation

Engine written in Haskell

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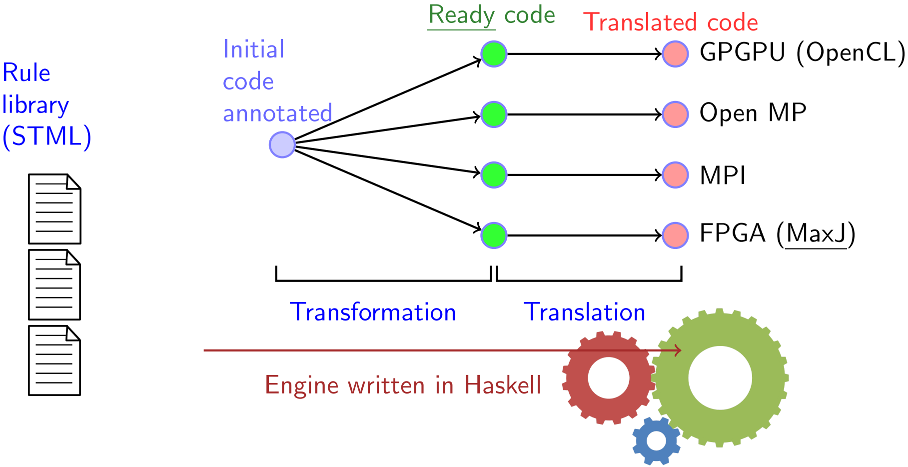

Rule library (STML)

Initial code annotated

Ready code

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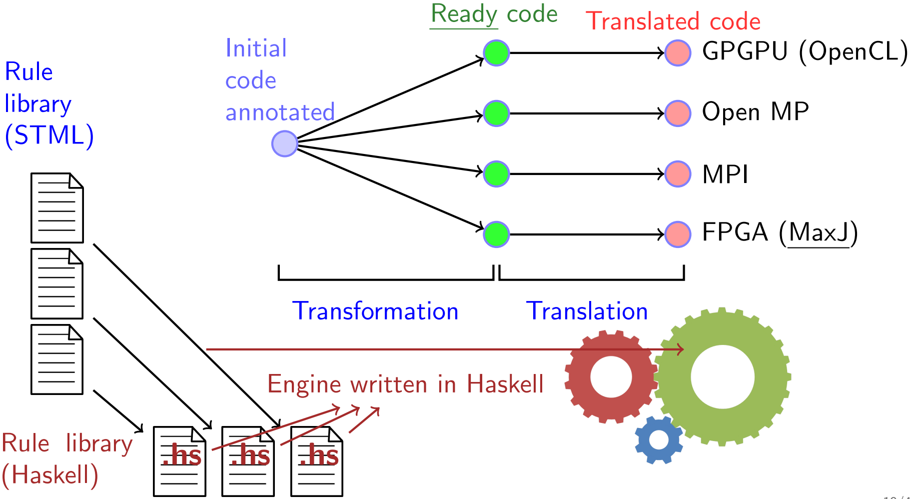

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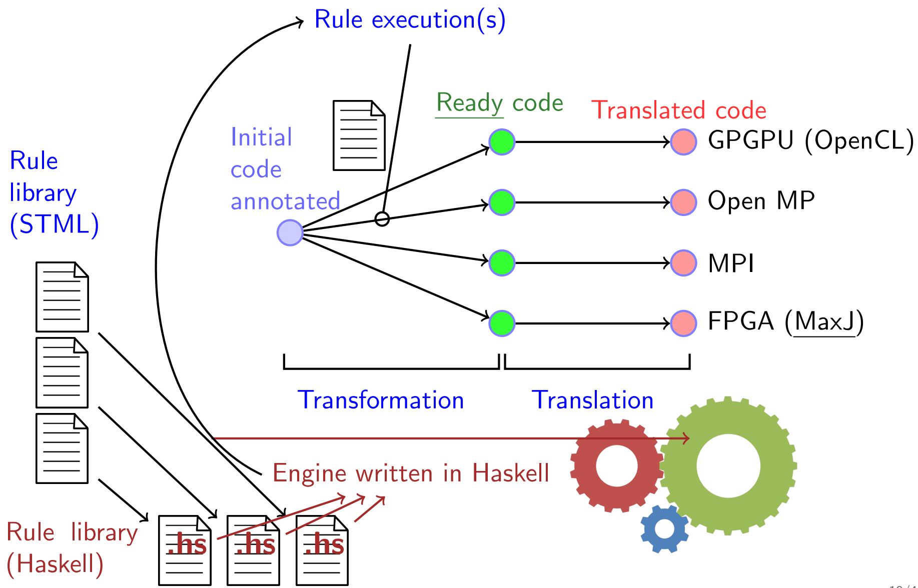


Rule Testing.

- How to ensure rules are correct?
  - Formal proofs possible (and ideal), but also resource-consuming.
- A set of automatic testers has been developed to ease the checking of the rules behavior.
- Perform several tests over the resulting code of each transformation step.
- Several strategies at the moment:
  - *n* random steps.
  - Random order, using each rule at most once.
  - Similar to last one, backtracking to previous states that could enable non-applied rules.
- Output:
  - Applied rules.
  - Not applied rules:
    - Because patterns or conditions not met.
    - Because they were not chosen (but could be applied).
  - In case of error: The failing rule and the concrete transformation step.

Rule Selection.

- Generally, several rules can be applied at a number of code locations.
- At any point, candidate rules can be:
  - applicable,
  - maybe (not) applicable,
  - definitely not applicable
- Selected rule(s) should improve code.

Interactive Rule Selection

- User chooses the transformation steps to apply.
- Meld and other specific tools (e.g. POGADE) help in this process.
- Useful to refine rules, perform specific transformations, do aggressive program refactoring.
- Scalability an issue.

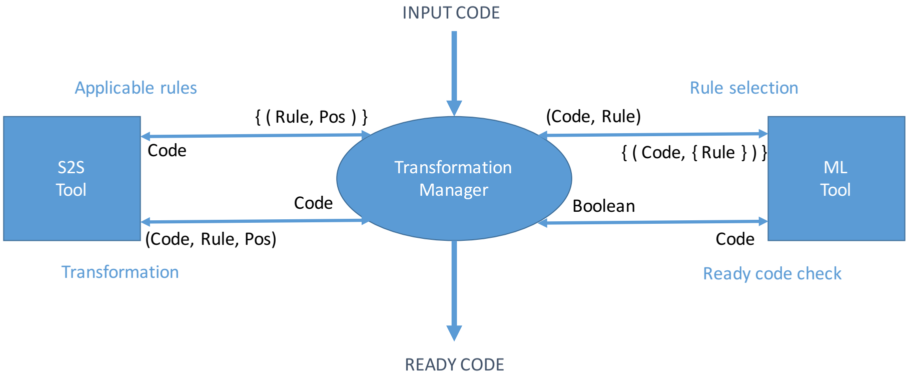
Rule Selection.

- We need a way to mechanize rule selection.
  - Select at each step the rule which reduces some metric → local minima
  - Explore a bounded number of possible rule applications
    - Too small → local minima
    - Too big → exponential explosion
- Additional issues
  - Inverse/involutive rules → infinite loops
  - Rules that duplicate code (e.g. unfolding) → same rule/different states

External Oracle to Select Rules

- Given code and set of applicable transformation steps, return which transformation step should be applied.
- Given code, return whether transformation can be assumed successfully finishd.

Source-to-Source Tool Interface.



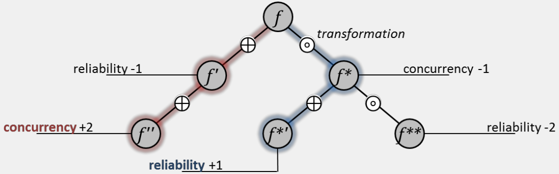
- All the communications are done using JSON.
- The s2s tool interface is also used by POGADE.
- A serialization of the AST, the applicable transformations and other relevant data is done when the s2s interfaces are used.

Machine Learning: Deciding Strategy

Problems to be Addressed.

- Rule-based transformation $\Longrightarrow$ **state-space exploration** problem.
  - Efficiently explore (**prune**) search space.
  - Define a **stop criteria**.
  - Improve **quality** of code.

Possible solution: heuristics to drive the search



- Heuristics which monotonically increase some metric would disallow sequences which temporarily generate code of lesser quality.
- Heuristics should “plan for” whole sequences or at least series of steps.

Non-Local Heuristics and Machine Learning.

- Don't come up with heuristics: likely complex and brittle.
- Synthesize (learn) them from existing, good examples.

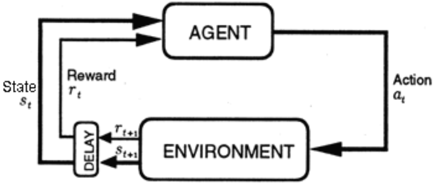
- ML generally operates on descriptions of real world.
- Program abstractions as descriptions of actual programs.
  - Should capture features of states (codes) in the search space.
  - Should reflect the changes performed by actions.
- Based on code features related with:
  - Control flow,
  - Data layout,
  - Data dependencies. . .
  - Also on code annotations (externally provided.)
- Note: previous works apply ML to e.g. compilation.

Abstraction: vector of code features (to be further enriched)

$\mathbb{N}$	$\mathbb{N}$	$\mathbb{N}$	$\mathbb{B}$	$\mathbb{B}$	$\mathbb{N}$	$\mathbb{B}$	$\mathbb{N}$	$\mathbb{B}$	$\mathbb{N}$	$\mathbb{N}$	$\mathbb{N}$	$\mathbb{N}$	$\mathbb{N}$	$\mathbb{N}$
max. nested loop depth	number of function calls	number of array write shifted within `for` loops	any irregular loop? (e.g., `break`, `continue`)	any global variable	number of `if` statements	`for` loop limits static for all loops?	number of SIMD loop	any `for` loop with `loop-schedule`?	number of loop invariant vars	number of loop hoisted var modifications	number of non-1D array	number of aux. var to access arrays	number of `for` loops	Non-normalized `for` loops

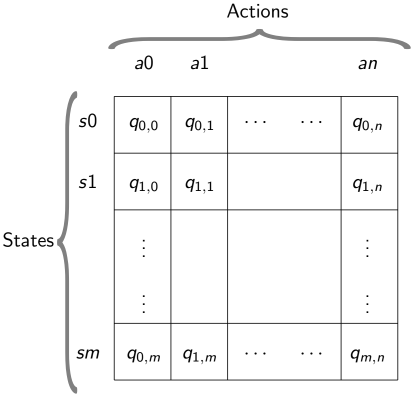
Reinforcement Learning.

- Large area of machine learning.
- Learn from sequences of states and transformations which may contain "counterproductive" steps.
- Reinforcement learning (RL):
  - Well-suited for problems with long-term (vs. short-term) rewards.
- Used by the transformation engine:
  - Reduce search space by applying "good" transformation sequences.
  - Handle sequences with intermediate "bad" steps (delayed reward).



RL Basics.

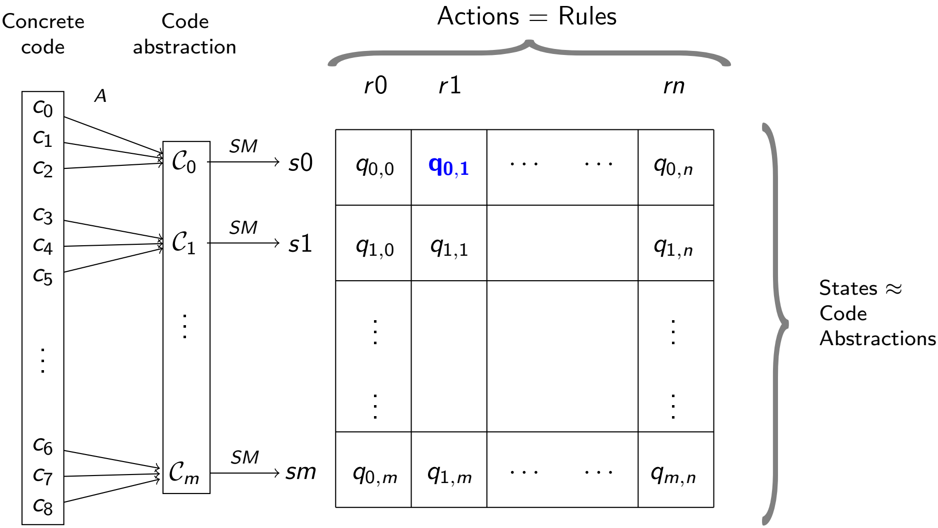
- RL learns from examples.
  - Sequences of stepwise changes from some initial state to some final state.
- Result: action-value matrix $Q(s_t, a_t)$
  - Determines, for each state, the relative profit of applying every action.
  - Action to apply: the one with highest profit.
- Q matrix filled with learning model
  - α: learning rate (new information)
  - γ: discount factor (future rewards)



	$a0$	$a1$		an
$s0$	$q_{0,0}$	$q_{0,1}$	$\cdots$ $\cdots$	$q_{0,n}$
$s1$	$q_{1,0}$	$q_{1,1}$		$q_{1,n}$
	$\vdots$			$\vdots$
	$\vdots$			$\vdots$
sm	$q_{0,m}$	$q_{1,m}$	$\cdots$ $\cdots$	$q_{m,n}$

$$Q(s_t, a_t) = \begin{cases} Q(s_t, a_t) + \alpha \cdot (r_{t+1} + \gamma \cdot Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)) & \text{if } s_t \textit{ not final} \\ Q_{init}(s_t, a_t) & \text{otherwise} \end{cases}$$

Code, State/Action Table, Rule Selection.



$r0$	$r1$		rn
$q_{0,0}$	$\mathbf{q_{0,1}}$	$\cdots$ $\cdots$	$q_{0,n}$
$q_{1,0}$	$q_{1,1}$		$q_{1,n}$
$\vdots$ $\vdots$			$\vdots$ $\vdots$
$q_{0,m}$	$q_{1,m}$	$\cdots$ $\cdots$	$q_{m,n}$

Search Space: Stopping.

- Stopping encoded in state-action table.
- Determine **stop criteria** for training sequences:
  - Is the current code ready to be translated into the target architecture?
  - If so, is the current code of quality enough?
- One possibility: at each step, check if transformed code can be used to generate correct platform-specific code.
  - Involves calling translator, platform-specific compiler.
  - Not practical – might take an exceedingly long time (e.g., in FPGAs).
  - Can not determine / measure optimality.
- Classification methods learned to classify good states to stop transforming.
  - Not a canonical form, but a shape which looks good enough.

Learning Example.

- A transformation sequence on a simple example.
  - Initial state: 2D convolution kernel.
  - Final code:
    - Well-suited to generate MaxJ (FPGA/DFE) code.
    - Learned by a classifier as a good final state for the translation phase.
  - Abstraction (vector of features) shown for each code state.
  - Transformation steps provided by expert programmer.
  - Code transformed in each step highlighted as:
    - before transformation
    - after transformation

Learning Example (Cont.).

- Initial code

```
// ABSTR: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 3, 2, 4, 0]

int dead_rows = K / 2;
int dead_cols = K / 2;

int normal_factor = K * K;

for (r = 0; r < N - K + 1; r++) {
  for (c = 0; c < N - K + 1; c++) {
    sum = 0;
    for (i = 0; i < K; i++) {
      for (j = 0; j < K; j++) {
        sum += input_image[r+i][c+j] * kernel[i][j];
      }
    }
    output_image[r+dead_rows][c+dead_cols] = (sum / normal_factor);
  }
 }
```

Learning Example (Cont.).

- Step 1 (Rule: ArrayFlatten)

```
// ABSTR: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 2, 2, 4, 0]

int dead_rows = K / 2;
int dead_cols = K / 2;

int normal_factor = K * K;

for (r = 0; r < N - K + 1; r++) {
  for (c = 0; c < N - K + 1; c++) {
    sum = 0;
    for (i = 0; i < K; i++) {
      for (j = 0; j < K; j++) {
        sum += input_image[(r+i)*(N - K + 1) + (c+j)] * kernel[i][j];
      }
    }
    output_image[r+dead_rows][c+dead_cols] = (sum / normal_factor);
  }
 }
```

Learning Example (Cont.).

- Step 2 (Rule: ArrayFlatten)

```
// ABSTR: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 1, 2, 4, 0]

int dead_rows = K / 2;
int dead_cols = K / 2;

int normal_factor = K * K;

for (r = 0; r < N - K + 1; r++) {
  for (c = 0; c < N - K + 1; c++) {
    sum = 0;
    for (i = 0; i < K; i++) {
      for (j = 0; j < K; j++) {
        sum += input_image[(r+i)*(N - K + 1) + (c+j)] * kernel[i*K+j];
      }
    }
    output_image[r+dead_rows][c+dead_cols] = (sum / normal_factor);
  }
 }
```

Learning Example (Cont.).

- Step 3 (Rule: ArrayFlatten)

```
// ABSTR: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 2, 4, 0]

int dead_rows = K / 2;
int dead_cols = K / 2;

int normal_factor = K * K;

for(r = 0; r < N - K + 1; r++) {
  for(c = 0; c < N - K + 1; c++) {
    sum = 0;
    for (i = 0; i < K; i++) {
      for (j = 0; j < K; j++) {
        sum += input_image[(r+i)*(N - K + 1) + (c+j)] * kernel[i*K+j];
      }
    }
    output_image[(r+dead_rows)*(N-K+1) + (c+dead_cols)] = (sum / normal_factor);
  }
 }
```

Learning Example (Cont.).

- Step 4 (Rule: CollapseFoorLoops)

```
// ABSTR: [2, 0, 0, 0, 0, 0, 1, 1, 0, 1, 1, 0, 2, 3, 0]

int dead_rows = K / 2;
int dead_cols = K / 2;

int normal_factor = K * K;

for (z = 0; z < (N - K + 1)*(N - K + 1); z++) {
    sum = 0;
    for (i = 0; i < K; i++) {
      for (j = 0; j < K; j++) {
        sum += input_image[((z / (N - K + 1))+i)*(N - K + 1) + ((z % (N - K +
              1))+j)] * kernel[i*K+j];
      }
    }
    output_image[((z / (N - K + 1))+dead_rows)*(N - K + 1) +
          ((z % (N - K + 1))+dead_cols)] = (sum / normal_factor);
}
```

Learning Example (Cont.).

- Mapping of states (S) to abstractions (A)

$S_0 = A(C_0)$: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 3, 2, 4, 0] (Initial)
$S_1 = A(C_1)$: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 2, 2, 4, 0]
$S_2 = A(C_2)$: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 1, 2, 4, 0]
$S_3 = A(C_3)$: [3, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 2, 4, 0]
$S_4 = A(C_4)$: [2, 0, 0, 0, 0, 0, 1, 1, 0, 1, 1, 0, 2, 3, 0] (Goal)

- Expert sequence (transition matrix)

	R_0	R_1
S_0	S_1	S_0
S_1	S_2	S_1
S_2	S_3	S_2
S_3	S_3	S_4
S_4	S_4	S_4

- Initial action-value table (Q)

	R_0	R_1	Best
C_0	1.0	1.0	-
C_1	1.0	1.0	-
C_2	1.0	1.0	-
C_3	1.0	1.0	-
C_4	1.0	1.0	-

Learning Example (Cont.).

- Simple training: 10 iterations, 3 interactions/iteration
- Learning params: $\alpha = 0.5$, $\gamma = 0.5$, $r_{t+1} = 1$ (final) | 0 (not final)

Iteration 1

	R_0	R_1	Best
C_0	0.9955	1.0	R_1
C_1	0.995	1.0	R_1
C_2	1.0	1.0	-
C_3	1.0	1.0	-
C_4	1.0	1.0	-

Iteration 3

	R_0	R_1	Best
C_0	0.9955	0.9881	R_0
C_1	0.995	1.0	R_1
C_2	1.0	1.0	-
C_3	1.0	1.4434	R_1
C_4	1.0	1.0	-

Iteration 5

	R_0	R_1	Best
C_0	0.9955	0.9881	R_0
C_1	0.9925	0.9955	R_1
C_2	1.2145	1.0910	R_0
C_3	1.0	1.4434	R_1
C_4	1.0	1.0	-

Iteration 10

	R_0	R_1	Best
C_0	1.1490	0.9881	R_0
C_1	1.2216	0.9905	R_0
C_2	1.5942	1.0910	R_0
C_3	0.995	1.9466	R_1
C_4	1.0	1.0	-

Implementation Details.

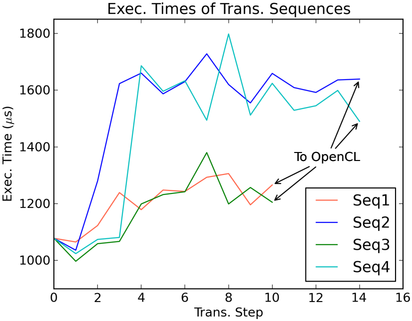
- Implemented in Python using two packages
- Scikit-learn: classification methods
  - Several machine learning algorithms
  - Good support and ample documentation
  - Widely used by the scientific community.
- PyBrain: reinforcement learning
  - Modular structure in classes (environment, actions, ...)
  - Extension of PyBrain classes to implement our approach

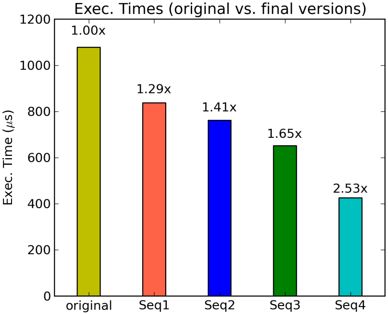
Preliminary Evaluation.

- Using cases from POLCA and UTDSP benchmark suite as training set.
- Featuring different algorithmic patterns (image processing):
  - Compress (JPG compression).
  - Edge detection (convolution).
  - RGB filter (image filter).
  - Threshold (image filter).
- Manually identified transformation sequences leading to **OpenCL**
- Simple **reward scheme** linked to efficiency (much higher for the best code).
- Evaluation using different examples, sharing patterns with training set:
  - 3D rotation.
  - Image difference.
  - Brightness change.
- Different aspects were satisfactorily evaluated:
  - Transformation process terminates, “good” final states reached.
  - RL learned different sequences which might share intermediate steps.
  - Transformations can start at any point in the learned sequences

Preliminary Evaluation.

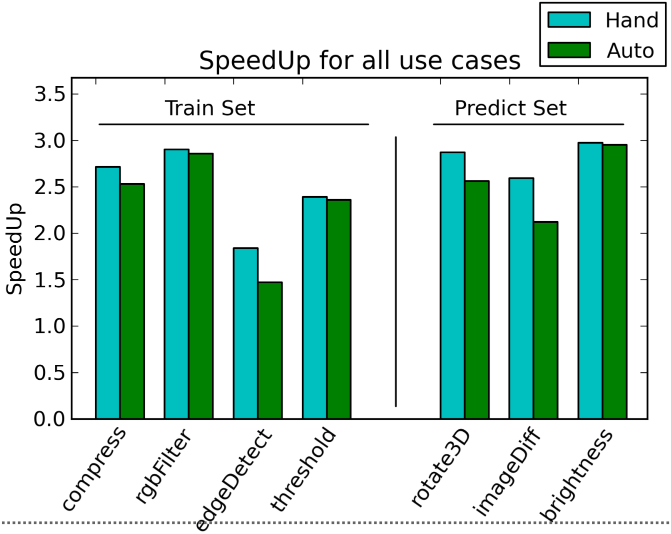
- Results to show the non-monotonic behavior of transformation sequences





Preliminary Evaluation.

- Evaluation of OpenCL code mechanically generated from learnt transformation sequences



Conclusions.

- Extensible, flexible rule-based framework for program transformation.
- Interface to external tools to select transformations to be enacted.
- Using machine learning-based oracle to guide rule selection.
- Preliminary evaluation (more around the corner!) satisfactory.

Future Steps.

- Add more (complex) transformation rules, evaluate on larger examples.
- Add more interfaces to external analysis tools.
  - Dependence analysis (e.g., polytope-based analyzers).
  - Reasoning over heap pointers (e.g., separation logic).
- Integrate profiling techniques → ease evaluation and give feedback.
- Increase training set, enhance code abstractions as needed.
- Use richer, non-functional measurements for RL.
  - Measures of optimality to better discriminate between possible final states based on performance.
- Explore using ML to decide best platform for a piece of code
  - E.g., use a single action-value table with several goals, select the best platform among the most reinforced sequences

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