On Policy Reuse: An Expressive Language for Representing and Executing Policies that Call Other Policies

Blai Bonet, Dominik Drexler, Hector Geffner

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Hector Geffner
RWTH Aachen University
Aachen, Germany

Linköping University
Linköping, Sweden

LINKÖPING UNIVERSITY

Alexander von HUMBOLDT STIFTUNG

RWTH AACHEN UNIVERSITY

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Motivation

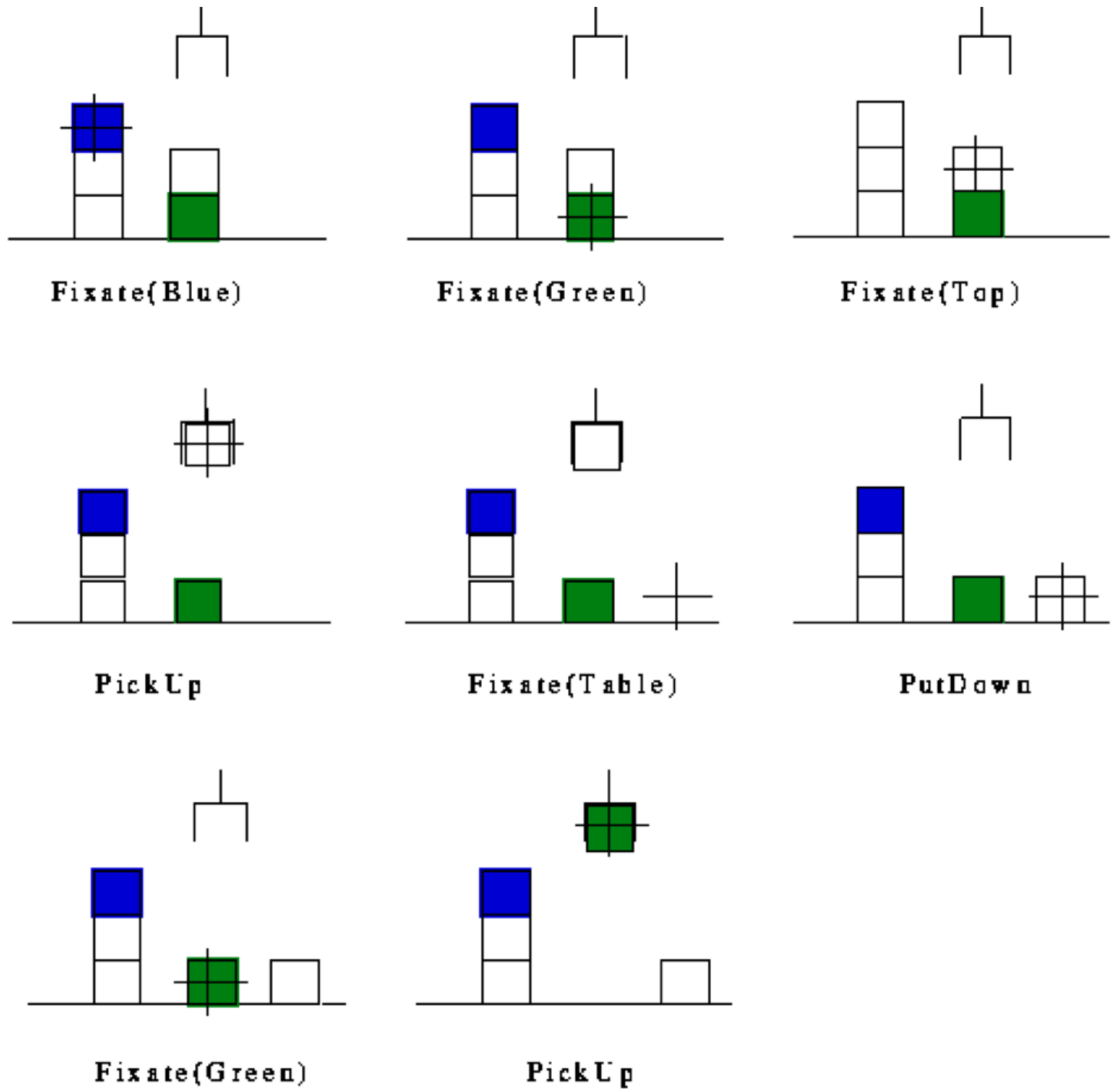
More expressive languages for **encoding** and **learning** general policies and sketches that support:

- **Reuse:** ability to call other policies by passing parameters
  - ▷ **Composition** and orchestration of subpolicies
  - ▷ **Bottom-up** construction of hierachies, as opposed to top-down
  - ▷ **Answers**: "Can policy for $on(x, y)$ be reused to construct arbitrary towers?"
- **Indexicals:** ability to refer to objects functionally, not by name
  - ▷ **Features** for capturing general policies/sketches simplified
  - ▷ **Active perception**: what to observe and when
  - ▷ **Determine action to do** without considering other actions/transitions

Related Research Threads

- **Planning programs and inductive programming** [2, 11, 12, 5].
  - ▷ Dreamcoder: Growing generalizable knowledge with program learning. K. Ellis *et al.*; 2020
  - ▷ Generalized planning as heuristic search. J. Segovia, S. Jimenez, A. Jonsson, AIJ 2021
- **General policies** [9, 10, 6], [13], [15, 8, 14].
  - ▷ Learning generalized policies using concept languages. M. Martin, H. G., KR 2000
- **Deictic representations** [4, 1, 3, 7].
  - ▷ David Chapman. Penguins can make cake. AI Magazine, 1989
  - ▷ Deictic codes for the embodiment of cognition. D. Ballard *et al.*, BBS 1997
  - ▷ The thing that we tried didn't work very well: Deictic representation in RL, S. Finney *et al.*, UAI 2022.

Example: Pick up green blocks; Ballard *et al.* 1997



This Work

Extensions to the language of **general policies** and **sketches**:

- Indexical pointers to objects
- Memory states
- Ground actions
- Modules that call other modules (reuse)

Example: General Policy for $clear(x)$

- **Policy** π for class $\mathcal{Q}_{clear}$ of problems with goal $clear(x)$ in Blocks:

$$\{\neg H, n > 0\} \mapsto \{H, n\downarrow\}$$
$$\{H, n > 0\} \mapsto \{\neg H\}$$

- **Features** $\Phi = \{H, n\}$: 'holding' and 'number of blocks above x'
- **Meaning:**
  - ▷ If $\neg H$ & $n > 0$, move to successor state where H holds and n **decreases**
  - ▷ If H & $n > 0$, move to successor state where $\neg H$ holds, n **doesn't change**
- **Shortcomings:**
  - ▷ Policy doesn't select actions directly; e.g. `pickup`(A), if A top block above x
  - ▷ Feature n for 'number of blocks above x', is "complex"

Example: New indexical policy for $clear(x)$

Concepts: used as features and to sample objects

- H_1 Boolean, whether block in $\mathfrak{r}_1$ is being held
- Table_1: Boolean, whether block in $\mathfrak{r}_1$ on table
- X: concept only contains given block x
- T_0: concept that contains block on block in register $\mathfrak{r}_0$ (if any)
- T_1: concept that contains block on block in register $\mathfrak{r}_1$ (if any)
- Initial memory state is always m_0; rule application change m_i

% Internal rules (update registers and internal memory; **no state transitions involved***)*

$r_0 = m_0 \,\|\, \{\text{X} > 0\} \mapsto \{\textit{Load}(\text{X}, \mathfrak{r}_0), \text{T}_0?\} \,\|\, m_1$ (Load x into register $\mathfrak{r}_0$)

$r_1 = m_1 \,\|\, \{\text{T}_0 > 0\} \mapsto \{\textit{Load}(\text{T}_0, \mathfrak{r}_1), \text{T}_1?\} \,\|\, m_2$ (Load block on x in $\mathfrak{r}_1$, if any)

$r_2 = m_2 \,\|\, \{\text{T}_1 > 0\} \mapsto \{\textit{Load}(\text{T}_1, \mathfrak{r}_1), \text{T}_1?\} \,\|\, m_2$ (Loop. Load block on $\mathfrak{r}_1$ in $\mathfrak{r}_1$

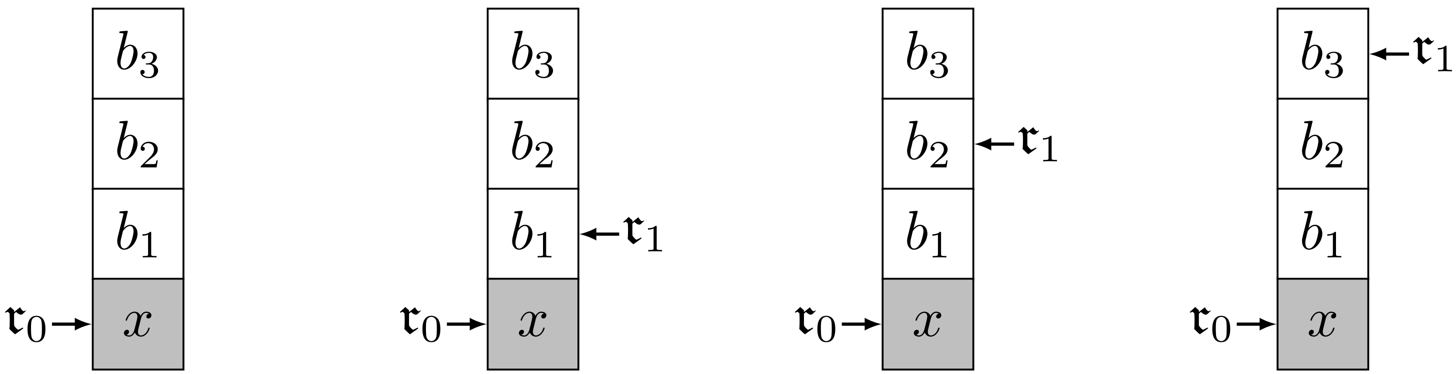
$r_3 = m_2 \,\|\, \{\text{T}_1 = 0\} \mapsto \{\} \,\|\, m_3$ until no such blocks, then

% External rules **(state transitions involved)**

$r_4 = m_3 \,\|\, \{\neg H_1\} \mapsto \{H_1\} \,\|\, m_3$ Unstack $\mathfrak{r}_1$)

$r_5 = m_3 \,\|\, \{H_1\} \mapsto \{\text{Table}_1, \neg H_1\} \,\|\, m_1$ (Put block being held on table, and loop)

Example: Execution of new indexical policy for $clear(x)$



$\mathsf{T}_0 = \{b_1\}$	$\mathsf{T}_0 = \{b_1\}$	$\mathsf{T}_0 = \{b_1\}$	$\mathsf{T}_0 = \{b_1\}$
	$\mathsf{T}_1 = \{b_2\}$	$\mathsf{T}_1 = \{b_3\}$	$\mathsf{T}_1 = \emptyset$

- Initially, load x in register $\mathfrak{r}_0$; equivalenty, **mark** x with $\mathfrak{r}_0$
- Put $\mathfrak{r}_1$ **mark** on block that is on the one marked with $\mathfrak{r}_0$
- Move $\mathfrak{r}_1$ **mark** to block that is on the one marked with $\mathfrak{r}_1$
- Until block with $\mathfrak{r}_1$ **mark** is clear and can be picked up directly

Extended Sketch/Policy Language

- **Concepts** C (unary predicates) used explicitly as Boolean features, $\mathsf{C} > 0$, numerical features C$\downarrow$, and for sampling objects

- **Registers** $\mathfrak{r}_i$ can be "loaded" with objects sampled from concepts; *Load*$(\mathsf{C}, \mathfrak{r}_i)$; registers are concepts too.

- **Memory states** m_i control flow along with Boolean conditions; e.g.,
  $m_1 \parallel \{C\} \mapsto \{E\} \parallel m_2$

- Rules with load effects or empty effects deemed as **internal rules**; others as **external rules**

- Memory states of internal rules and external rules different

- See paper for **formal syntax** and **semantics**

Modules: Reusing Policies

- Policies and sketches wrapped into *modules*
- **Modules may call other modules and do recursion passing parameters**
- Execution model uses a **stack** and caller/callee protocol, as in prog. languages
- Orchestration of collections $\{\texttt{mod}_0, \texttt{mod}_1, \texttt{mod}_2, \ldots\}$ of modules
- Additional external rules in modules:
  - ▷ **Call rules:** $m \,\|\, C \mapsto \texttt{mod}(\mathsf{C}_1, \mathsf{C}_2, \ldots, \mathsf{C}_k) \,\|\, m'$ where C is condition, and m and m' are memory states, to call mod with $\mathsf{C}_1, \ldots, \mathsf{C}_k$ as arguments
  - ▷ **Do rules:** $m \,\|\, C \mapsto \texttt{act}(\mathsf{C}_1, \mathsf{C}_2, \ldots, \mathsf{C}_k) \,\|\, m'$ to apply a **ground action** $\texttt{act}(o_1, o_2, \ldots, o_k)$ with objects $o_i \in \mathsf{C}_i$, for $i = 1, 2, \ldots, k$

Example: Modules for $on(x, y)$

Module $\texttt{On}(\mathsf{X}, \mathsf{Y})$:

$r_0 \;=\; m_0 \,\|\, \{\neg On\} \mapsto \texttt{Clear}(\mathsf{X}) \,\|\, m_1$ (Call `Clear` with argument X)

$r_1 \;=\; m_1 \,\|\, \{\} \mapsto \texttt{Clear}(\mathsf{Y}) \,\|\, m_2$ (Call `Clear` with argument Y)

$r_2 \;=\; m_2 \,\|\, \{\neg H_{\mathsf{X}}\} \mapsto \{H_{\mathsf{X}}\} \,\|\, m_3$ (Pick block x, either `unstack` or `pickup`)

$r_3 \;=\; m_3 \,\|\, \{H_{\mathsf{X}}\} \mapsto \texttt{stack}(\mathsf{X}, \mathsf{Y}) \,\|\, m_3$ (Apply `stack` to put x on y)

Module $\texttt{Clear}(\mathsf{X})$:

$r_0 \;=\; m_0 \,\|\, \{\mathsf{X} > 0\} \mapsto \{\mathit{Load}(\mathsf{X}, \mathfrak{r}_0), \mathsf{T}_0?\} \,\|\, m_1$ (Load x in register $\mathfrak{r}_0$)

$r_1 \;=\; m_1 \,\|\, \{\mathsf{T}_0 > 0\} \mapsto \{\mathit{Load}(\mathsf{T}_0, \mathfrak{r}_1), \mathsf{T}_1?\} \,\|\, m_2$ (Load block above x in $\mathfrak{r}_1$, if any)

$r_2 \;=\; m_2 \,\|\, \{\mathsf{T}_1 > 0\} \mapsto \{\mathit{Load}(\mathsf{T}_1, \mathfrak{r}_1), \mathsf{T}_1?\} \,\|\, m_2$ (Loop. Load block above $\mathfrak{r}_1$ in $\mathfrak{r}_1$)

$r_3 \;=\; m_2 \,\|\, \{\mathsf{T}_1 = 0\} \mapsto \{\} \,\|\, m_3$ (Go to external rules)

$r_4 \;=\; m_3 \,\|\, \{\neg H\} \mapsto \texttt{unstack}(\mathfrak{r}_1, \mathsf{B}) \,\|\, m_3$ (Apply `unstack` to pick $\mathfrak{r}_1$)

$r_5 \;=\; m_3 \,\|\, \{H\} \mapsto \texttt{putdown}(\mathfrak{r}_1) \,\|\, m_1$ (Apply `putdown` to put $\mathfrak{r}_1$ on table)

Example: Building One Tower with Module $\texttt{Tower}(\mathbf{O}, \mathbf{X})$

- Objective is to build tower $\bigwedge_{i=1}^{k} on(x_i, x_{i-1}) \wedge ontable(x_0)$
- Role argument $\mathsf{O} = \{(x_i, x_{i-1}) \mid i = 1, \ldots, k\}$
- X is concept for *lowest* block in tower that is *misplaced*
- M is concept for block to be placed on $\mathfrak{r}_0$ according to O (if any)
- W is concept for block below $\mathfrak{r}_0$ according to O (if any)

Module $\texttt{Tower}(\mathsf{O}, \mathsf{X})$:

$$r_0 \;=\; m_0 \,\|\, \{X > 0\} \mapsto \{\textit{Load}(\mathsf{X}, \mathfrak{r}_0), \mathsf{M}?, \mathsf{W}?\} \,\|\, m_1 \qquad \text{(Load X into register } \mathfrak{r}_0\text{)}$$

$$r_1 \;=\; m_1 \,\|\, \{W = 0\} \mapsto \texttt{On-Table}(\mathfrak{r}_0) \,\|\, m_2 \qquad (\texttt{On-Table} \text{ to put X on table})$$

$$r_2 \;=\; m_1 \,\|\, \{W > 0\} \mapsto \texttt{On}(\mathfrak{r}_0, \mathsf{W}) \,\|\, m_2 \qquad (\texttt{On}(\mathfrak{r}_0, \mathsf{W}) \text{ to well-place } \mathfrak{r}_0)$$

$$r_3 \;=\; m_2 \,\|\, \{M > 0\} \mapsto \texttt{Tower}(\mathsf{O}, \mathsf{M}) \,\|\, m_3 \qquad \text{(Continue building tower from M)}$$

Example: Building Many Towers

- Argument O is **role** that contains the pairs describing the towers to build
- L is concept for *lowest misplaced blocks* according to O

Module `Blocks`(O):

$$r_0 \;=\; m_0 \,\|\, \{\mathsf{L} > 0\} \mapsto \{\mathit{Load}(\mathsf{L}, \mathfrak{r}_0)\} \,\|\, m_1 \qquad \text{(Load X into register } \mathfrak{r}_0\text{)}$$

$$r_1 \;=\; m_1 \,\|\, \{\} \mapsto \mathtt{Tower}(\mathsf{O}, \mathfrak{r}_0) \,\|\, m_0 \qquad \text{(Build tower on } \mathfrak{r}_0\text{)}$$

Summary. Future

Language extensions for **encoding** and **learning** general policies and sketches:

- **Reuse** and **bottom up** composition of policies
- Don't **learn policies from scratch;** resue those learned
- **Indexicals** (registers) simplify features, determine actions to do, active perception
- **Interpreter** available, but not learning yet
- **Limitations.** Language is:
  - ▷ "too much": hard to learn and verify, too many alternative encodings
  - ▷ "too little": flexibility lacking for handling negative interactions
- One step; others to follow

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