# Implementation Guide: SOUL Motivation Framework

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## 1 Literature Review

We have identified six practical schools of agent motivation:

- **Intrinsic Motivation in RL**: Curiosity and surprise as auxiliary rewards to drive exploration in sparse environments (Schmidhuber, 2010; Pathak et al., 2017).
- **Information-Theoretic Drives**: Maximizing mutual information, novelty, and empowerment signals (Klyubin et al., 2005; Salge et al., 2014; Goertzel, 2024).
- **Competence-Progress Models**: Rewarding measurable learning progress toward self-generated subgoals to form a self-curriculum (Oudeyer & Kaplan, 2007).
- **Homeostatic/Drive-Reduction**: Minimizing internal variables (e.g., prediction error) via cybernetic drives (Hull, 1943; Friston, 2010).
- **Cognitive Architectures**: Embedding scalar drives into symbolic cycles (Soar's operator preferences; ACT-R's Expected Value of Control; Goertzel, 2024) for precise control updates.
- **Developmental-Robotics Hybrids**: Combining maturational constraints with competence progress to emulate developmental curricula (Lungarella et al., 2003).

## 2 Mathematical Foundations and Architectural Decisions

### 2.1 The Motivation Vector

At the heart of the SOUL Motivation Framework is the hidden internal state, the Motivation Vector:

$$\mathbf{s}_t = [s_c, s_u, s_h]$$

where $s_c$ is competence, $s_u$ is novelty/surprise, and $s_h$ is homeostasis. This vector is updated after every interaction and drives all agent actions. In code, it is maintained as a Python dataclass and is never exposed to the LLM.

## 2.2 Motivation Vector Updates

- **Competence Progress:**

$$\Delta_c = p_g(t) - p_g(t-1), \quad s_c \leftarrow \mathrm{clip}(s_c + \alpha\Delta_c, 0, 1)$$

  where $p_g(t)$ is the agent's measured performance at time $t$.

- **Novelty/Surprise:**

$$\mathrm{novel}(t) = 1 - \frac{\mathbf{e}(t)\cdot\mu_{t-1}}{\|\mathbf{e}(t)\|\,\|\mu_{t-1}\|}, \quad s_u \leftarrow \mathrm{clip}(s_u + \alpha\,\mathrm{novel}(t), 0, 1)$$

  where $\mathbf{e}(t)$ is the current context embedding and $\mu_{t-1}$ is the rolling mean.

- **Homeostatic Decay:**

$$s_h \leftarrow (1-\delta)s_h + \delta$$

  This ensures $s_h$ gently returns to baseline.

## 2.3 Meta-Graph and Rule Engine

The agent maintains a symbolic meta-graph $G$ (a directed graph of rewrite rules $R$ and meta-rules $M$). Each node represents a pattern or rule, and edges encode transformations or relationships. In Python, this is implemented with `networkx.DiGraph`.

## 2.4 Thresholded Nudge and Confidence

At each step, the agent computes a confidence score $C_t$:

$$C_t = f_{\mathrm{match}}(x_t, G, \mathbf{s}_t)$$

where $f_{\mathrm{match}}$ is a similarity or density function over meta-graph patterns and the current state. The agent compares $C_t$ to a dynamic threshold $\tau_t$:

$$\text{If} \quad C_t \geq \tau_t \quad \text{then nudge; else remain silent (null action)}$$

**Concrete Example:** If $C_t$ is computed as the softmax of pattern matches in $G$ weighted by $\mathbf{s}_t$, and $\tau_t$ is set adaptively (e.g., as a running quantile), then the agent only acts when it is sufficiently confident.

## 2.5 Perception–Cognition–Action Loop

The agent's operation at each time $t$ is:

$$\begin{aligned}
\text{Perceive:} \quad & y_t = \mathrm{Perceive}(x_t) \\
\text{Update:} \quad & \mathbf{s}_{t+1} = \mathrm{UpdateMotivation}(\mathbf{s}_t, y_t) \\
\text{Record:} \quad & G_{t+1} = \mathrm{UpdateMetaGraph}(G_t, x_t, y_t) \\
\text{Confidence:} \quad & C_{t+1} = f_{\mathrm{match}}(x_{t+1}, G_{t+1}, \mathbf{s}_{t+1}) \\
\text{Action:} \quad & a_{t+1} = \begin{cases} \mathrm{HarvestAxiom}(G_{t+1}, x_{t+1}) & \text{if } C_{t+1} \geq \tau_{t+1} \\ \varnothing & \text{otherwise} \end{cases}
\end{aligned}$$

*Explanation:* $a_{t+1}$ is either a harvested axiom/rule (to be injected as a nudge) or the null action $\varnothing$ (agent remains silent).

### 2.6 Subgoal Discovery

If $s_c$ stagnates or $s_u$ spikes, the agent auto-discovers new subgoals by clustering novel contexts in $G$ and generating new rules. This enables adaptive exploration.

### 2.7 Discrete Generative Core and Error Signals

Instincts and policies are encoded as rewrite rules in $G$. The agent predicts a distribution $p_t(m)$ over outcomes, observes $q_t(m)$, and computes error:

$$e_t = D_{\mathrm{KL}}(q_t \| p_t)$$

This error drives reward and learning:

$$r_t^{\mathrm{int}} = -e_t, \qquad r_t^{\mathrm{ep}} \propto \sum_m q_t(m) \log \frac{1}{p_t(m)}$$

### 2.8 Meta-Rule Self-Modification

Meta-rules $M$ rewrite the rule graph itself:

$$m_i \leftarrow \underset{m' \in \mathcal{N}(m_i)}{\arg\min}\; e_t\big(R,\, M \setminus \{m_i\} \cup \{m'\}\big)$$

### 2.9 Wasserstein Natural Gradient

Parameterize rule-distribution $p(\xi)$ and update via:

$$\xi_{k+1} = \xi_k - h\, G(\xi_k)^{-1}\, \nabla_\xi F\big(p(\xi_k)\big)$$

where $G$ is the Laplacian from the rule graph.

### 2.10 Neural–Symbolic Hybrid and Memory

Continuous predictive-coding nets (vision and motor) run beneath the discrete core, exchanging features/actions. Long-term memory is implemented via vector stores (e.g., `faiss`, `chromadb`) for retrieval and adaptation.

### 2.11 LLM Pre-Prompting and Naturalization

When the agent nudges, it injects symbolic axioms/rules into the LLM prompt. The LLM is pre-prompted to interpret these in MeTTa or similar syntax and translate their intent into natural language or actions.

### 2.12 Genetic Mixing and Policy Sharing

Hyperparameters $(\alpha, \delta, \tau_c, \tau_u)$ are encoded as arrays and can be evolved via genetic algorithms (e.g., `DEAP`, `pygad`), enabling agent societies to mix and share policies and meta-graphs.

### 2.13 Concrete Python Mapping

- **Motivation Vector:** Python `dataclass` with fields for $s_c$, $s_u$, $s_h$.
- **Rule Graph:** `networkx.DiGraph` with nodes for rules/meta-rules.
- **Neural Nets:** `torch.nn.Module` or `jax` models for predictive coding.
- **Memory:** `faiss` or `chromadb` vector store.
- **Hyperparameters:** Numpy array or genetic algorithm chromosome.

## 3 Null Action and Silent Learning

*If the confidence $C_t$ does not exceed the threshold $\tau_t$, the agent performs the null action $\varnothing$, i.e., it remains silent and continues to observe, record, and learn without intervening.*

## 4 Implementation Guide

Below are concrete steps, with Python library suggestions.

- **Competence-Progress Core**: Track competence gains $\Delta_c$ on self-generated subgoals, updating $s_c \in [0, 1]$ via

$$s_c \leftarrow \text{clip}(s_c + \alpha\,\Delta_c,\ 0, 1)$$

- **Novelty/Surprise Seeding**: Compute novelty as cosine distance of new embedding $\mathbf{e}(t)$ to recent mean $\mu_{t-1}$,

$$\text{novel}(t) = 1 - \frac{\mathbf{e}(t) \cdot \mu_{t-1}}{\|\mathbf{e}(t)\|\,\|\mu_{t-1}\|}, \quad s_u \leftarrow \text{clip}(s_u + \alpha\,\text{novel}(t),\ 0, 1)$$

- **Homeostatic Decay**: Maintain stability $s_h$ toward 1 via

$$s_h \leftarrow (1 - \delta)\,s_h + \delta$$

- **Thresholded Nudge Mechanism**: At each step, the agent computes a confidence score $C_t$ based on the match between the current context $x_t$, the meta-graph $G$, and the motivation vector $\mathbf{s}_t$:

$$C_t = f_{\text{match}}(x_t, G, \mathbf{s}_t)$$

  The agent compares $C_t$ to a dynamic threshold $\tau_t$:

$$\text{If} \quad C_t \geq \tau_t \quad \text{then nudge; else remain silent (null action)}$$

*Explanation:* $f_{\text{match}}$ may be a similarity or density function over meta-graph patterns, and $\tau_t$ can be static or adaptively tuned.

- **Perception–Cognition–Action Loop**: The agent's operation at each time $t$ can be mathematically expressed as:

$$\begin{aligned}
\text{Perceive:} \quad & y_t = \text{Perceive}(x_t) \\
\text{Update:} \quad & \mathbf{s}_{t+1} = \text{UpdateMotivation}(\mathbf{s}_t, y_t) \\
\text{Record:} \quad & G_{t+1} = \text{UpdateMetaGraph}(G_t, x_t, y_t) \\
\text{Confidence:} \quad & C_{t+1} = f_{\text{match}}(x_{t+1}, G_{t+1}, \mathbf{s}_{t+1}) \\
\text{Action:} \quad & a_{t+1} = \begin{cases} \text{HarvestAxiom}(G_{t+1}, x_{t+1}) & \text{if } C_{t+1} \geq \tau_{t+1} \\ \varnothing & \text{otherwise} \end{cases}
\end{aligned}$$

  *Explanation:* $a_{t+1}$ is either a harvested axiom/rule (to be injected as a nudge) or the null action $\varnothing$ (agent remains silent).

- **Discrete Generative Core**: Represent "instincts" as a *metagraph* of rewrite rules $R$, inducing a predicted distribution $p_t(m)$ over outcomes. Measure error [1]

$$e_t = D_{\text{KL}}(q_t \| p_t)$$

- **Reward Signals**: Combine instrumental $r_t^{\text{int}} = -e_t$ and epistemic $r_t^{\text{ep}} \propto \sum_m q_t(m) \log \frac{1}{p_t(m)}$ to guide local rule edits.[1]

- **Meta-Rule Self-Modification**: Define meta-rules $M$ that pattern-match on $R$ and refactor complex rules. Local meta-update:

$$m_i \leftarrow \underset{m' \in \mathcal{N}(m_i)}{\arg\min}\ e_t\big(R,\, M \setminus \{m_i\} \cup \{m'\}\big) \quad [1]$$

  Meta-rules undergo the same reward-driven selection as object-level rules.

- **Wasserstein Natural Gradient**: Parameterize rule-distribution $p(\xi)$ and update via the optimal-transport natural gradient:[1]

$$\xi_{k+1} = \xi_k - h\, G(\xi_k)^{-1}\, \nabla_\xi F\big(p(\xi_k)\big)$$

  with metric tensor $G$ from the measure-dependent Laplacian on the rule graph.

- **Neural–Symbolic Hybrid**: Two continuous predictive-coding nets (vision and motor) run beneath the discrete core (a *metagraph* of self-transforming codelets), passing symbolic features and actions in a closed-loop.[1]

**Null Action and Silence:** *If the confidence $C_t$ does not exceed the threshold $\tau_t$, the agent performs the null action $\varnothing$, i.e., it remains silent and continues to observe, record, and learn without intervening.*

## 5 Implementation Guide

Below are concrete steps, with Python library suggestions.

### 5.1 Core Data Structures

- Use `numpy` for vector operations and embeddings.
- Use `networkx` to represent the metagraph of rewrite rules and compute Laplacians.
- Store agent state in a simple `dataclass`:

```
from dataclasses import dataclass
@dataclass
class State:
    competence: float = 0.0
    curiosity:  float = 0.0
    stability:  float = 1.0
```

### 5.2 Novelty Detector

- Implement rolling mean with `collections.deque` and cosine distance via `scipy.spatial.distance.cos`

### 5.3 Rewrite-Rule Engine

- Model rules as Python objects mapping pattern graphs to outputs.
- Use `networkx` pattern-matching or custom graph algorithms for rule application.
- Derive $p_t(m)$ by sampling or counting rule firings over stochastic selections (e.g., softmax weights in `torch`).

### 5.4 Information-Theoretic Error

- Compute KL divergence with `scipy.stats.entropy(q, p)`.

### 5.5 Reward & State Update Loop

1. Collect feedback score $r(t)$ via environment simulation or user rating.
2. Update `State` (Motivation Vector) using the mathematical formulas above, with learning rate `alpha`.
3. Compute confidence $C_t$ and compare to threshold $\tau_t$; if $C_t \geq \tau_t$, harvest and inject a nudge (axiom/rule) from the meta-graph.
4. If nudging, prepend the harvested axiom/rule to the user query and invoke the LLM (e.g., via `openai` or `transformers`), relying on a pre-prompt for interpretation.

5. If not nudging, remain silent and continue to observe, record, and update internal state.

**Example:** In Python, this loop is implemented as a function that updates the Motivation Vector, computes confidence, and either calls a nudge-injection routine or skips to the next observation.

### 5.6 Meta-Rule Implementation

- Represent meta-rules as rules over the rule-graph using `networkx`.
- Define neighborhood $\mathcal{N}(m_i)$ of small metagraph edits.
- Apply the meta-rule update formula in your training loop alongside rule edits.

### 5.7 Natural Gradient Optimization

- Install `pot` (Python Optimal Transport) for Wasserstein solvers.
- Build ground metric matrix $(\omega_{ij})$ from rule-graph distances.
- Construct measure-dependent Laplacian via NetworkX weights.
- Compute parameter Jacobians with `autograd` or manual derivatives.
- Perform updates using `numpy.linalg.pinv` for pseudoinverse.

### 5.8 Continuous Predictive-Coding Nets

- Use `PyTorch` or `JAX` to implement NGC-style layers:

$$z \leftarrow z + \beta\big(-\gamma z + (E \cdot e) \odot \phi'(z) - e\big)$$

- Leverage `torch.nn.Module` for vision and arm nets.
- Optimize with local Hebbian-like or standard optimizers (SGD) per PC update.

### 5.9 Genetic Tuning (Optional)

- Represent hyperparameters $(\alpha, \delta, \tau_c, \tau_u)$ as a NumPy array.
- Use `DEAP` or `pygad` for crossover and mutation over logged performance metrics.

### 5.10 Vector Stores and Long-Term Memory

- Integrate `faiss` or `chromadb` for storing past contexts/embeddings.

## 6 Conclusion

This guide unifies seminal research, architectural principles, and practical Python tools to implement SOUL's Motivation Framework. By following it, you'll build agents that self-modify, learn from surprise and progress, and nudge LLMs with precise, adaptive prompts.

## References


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