NOVAMENTE

A Practical Architecture for Artificial General Intelligence

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Biomind LLC
Artificial General Intelligence Research Institute
Virginia Tech, Applied Research Lab for National and Homeland Security
The Novamente Project

- **Long-term goal:**
  - creating "artificial general intelligence" approaching and then exceeding the human level
  - to be approached via a series of incremental phases
    - Learning programme inspired by human developmental psychology
    - The system is taught via its embodiment in a 3D simulation world

- **Novamente AI Engine:** an integrative AI architecture
  - Overall architecture inspired by cognitive science
  - a "weighted labeled hypergraph" knowledge representation
    - smoothly spans perception, cognition and action
    - Aspects in common with semantic nets and attractor neural nets
  - Learning via computer science algorithms:
    - evolutionary programming (a special kind of EDA)
    - probabilistic inference (Probabilistic Logic Networks)
  - efficient, scalable C++/Linux implementation

- **Currently parts of the Novamente codebase are being used for commercial projects**
  - natural language processing
  - biological data analysis
Overview Papers

• *The Novamente AI Engine*
  – IJCAI Workshop on Intelligent Control of Agents, Acapulco, August 2003

• *Novamente: An Integrative Architecture for Artificial General Intelligence*
  – AAAI Symposium on Achieving Human-Level Intelligence Through Integrated Systems and Research, Washington DC, October 2004

• *Patterns, Hypergraphs and General Intelligence*
  – World Congress on Computational Intelligence, Vancouver CA, July 2006

• *Chapter on Novamente in*
  – *Artificial General Intelligence* volume, Springer Verlag, 2006
Novamente-Related Books-in-Progress

- **The Hidden Pattern**
  - Related philosophy of mind
  - *In press; to appear 2006*

- **Probabilistic Term Logic**
  - *In final editing stage; to be submitted 2006*

- **Engineering General Intelligence**
  - *In final editing stage*
  - Reviews the overall NM design
  - May or may not be submitted (AI Safety concerns)

- **Artificial Cognitive Development**
  - Developmental psychology for Novamente and other AGIs
  - *In preparation*
The Grand Vision
- Conceptual Background
- Teaching Approach
- Knowledge Representation
- Software Architecture
- Learning Dynamics

The Current Reality
- Implemented Components
- AGISim Experiments
- NLP Experiments

The Path Ahead
Novamente:

The Grand Vision
Conceptual Background: Probabilistic Patternism

- Founded on a “patternist philosophy of mind”
- An intelligent system is conceived as a system for recognizing patterns in the world and in itself
- Probability theory is used as a language for quantifying and relating patterns
- Logic (term, predicate, combinatory) is used as a base-level language for expressing patterns
- Self-analysis allows the system to recognize and utilize patterns existing emergently among numerous logical expressions
Conceptual Background: Novamente Learning Dynamics

- **Evolutionary learning** is used to generate speculative new patterns

- **Logical inference** is used to systematically extrapolate known patterns
  - Accounting appropriately for uncertainty in inference is critical

- Simpler, statistical pattern mining algorithms are also incorporated
Conceptual Background: Definition of Intelligence

- Intelligence is considered as the ability to achieve complex goals in a complex environment.

- Goals are achieved via recognizing probabilistic patterns of the form “Carrying out procedure P in context C will achieve goal G.”
The Structure of Intelligence, Springer-Verlag, 1993

The Evolving Mind, Gordon and Breach, 2003

Chaotic Logic, Plenum Press, 1994

From Complexity to Creativity, Plenum Press, 1997

Creating Internet Intelligence, Kluwer Academic, 2001

The Hidden Pattern, Brown Walker Press, 2006
The Hidden Pattern presents a novel philosophy of mind, intended to form a coherent conceptual framework within which it is possible to understand the diverse aspects of mind and intelligence in a unified way. The central concept of the philosophy presented is the concept of "pattern": minds and the world they live in and co-create are viewed as patterned systems of patterns, evolving over time, and various aspects of subjective experience and individual and social intelligence are analyzed in detail in this light.

Many of the ideas presented are motivated by recent research in artificial intelligence and cognitive science, and the author's own AI research is discussed in moderate detail in one chapter. However, the scope of the book is broader than this, incorporating insights from sources as diverse as Vedantic philosophy, psychedelic psychotherapy, Nietzschean and Peircean metaphysics and quantum theory. One of the unique aspects of the patternist approach is the way it seamlessly fuses the mechanistic, engineering-oriented approach to intelligence and the introspective, experiential approach to intelligence.
The Hidden Pattern:
Contents

1. Meta-Philosophy
2. Kinds of Minds
3. Universal Mind
4. Intelligence
5. Experience
6. Four Levels of Mind
7. Complexity
8. Quantum Reality and Mind
9. Free Will
10. Emotion
11. Autopoiesis
12. Evolution
13. Science
14. Language
15. Toward Artificial Minds
16. Post-Embodied AI
17. Causation
18. Belief and Self Systems
19. Creative Intuition
20. Mindfulness and Evil
21. Immortality
22. Compassion and Ethics

Appendices
A1. Toward a Mathematical Theory of Pattern
A2. Toward a Mathematical Theory of Mind
A3. Notes on the Formalization of Causal Inference
AI Teaching Methodology

- Embodiment
- Post-embodiment
- Developmental Stages
The Power of Embodiment

Embodiment (real or virtual) provides a would-be AGI with

- Symbol grounding
  - Most crucially: grounding of subtle words like prepositions

- An effective medium for learning complex cognitive skills
  - attention allocation
  - procedure-learning
  - inference control

- A sense of self
  - Critical for cognition as well as mental health

- Empathy with humans
AGISim: An Open-Source Simulation Environment for AGI

- AI systems can sense and act in real-time via embodiment in a 3D virtual world
- Uses CrystalSpace (open-source game engine) for visualization
- Provides AI systems with multisensory inputs
  - visual inputs at varying levels of granularity: pixels, polygons or objects
  - hearing, touch, proprioception, …
- Integration with natural language interface for fluid, situated communication
- Suitable for teaching/learning based on a developmental-psychology-based methodology
- Compatible with Novamente but usable by any AI system via a simple sockets-based protocol
AI systems may viably synthesize knowledge gained via various means

- virtually embodied experience
  - AGISim

- physically embodied experience
  - Robotics

- explicit encoding of knowledge in natural language

- ingestion of databases
  - WordNet, FrameNet, Cyc, etc.
  - quantitative scientific data

Post-Embodied AI
Infantile Stage: making sense of & achieving simple goals in sensorimotor reality
Concrete Operational Stage: rich variety of learned mental representations and operations thereon
Formal Stage: abstract reasoning & hypothesizing
Reflexive Stage: deep understanding & control of self structures & dynamics
Full Self-Modification
**Full Self-Modification**

detailed understanding of its own AI algorithms and structures

**Reflexive Stage**

**Formal Stage**

- theorem-proving, scientific discovery

**Concrete Operational Stage**

- NL conversation

**Infantile Stage**

- AGISim

**Scientific data-sets**

**Mizar Math Database**

**Advanced Internet Text**

**Simple Internet Text**

**Link Parser**

**Rule-based NLP**

**WordNet**
Artificial Cognitive Development:

Contents

(with Stephan Vladimir Bugaj, Ari Heljakka. ??)

1. Cognitive Development from a Systems Theory Perspective
2. Human versus Artificial Developmental Psychology
3. Object Recognition and Object Permanence
4. Grounding Semantic Primitives
5. Building the Phenomenal Self
6. Experiential Language Learning
7. Learning “Theory of Mind”
8. Learning Conservation Laws
9. Learning Ethical Behavior
Knowledge Representation
Novamente’s “Atom Space”

- Atoms = Nodes or Links
- Atoms have
  - Truth values (probability + weight of evidence)
  - Attention values (short and long term importance)
- The Atomspace is a weighted, labeled hypergraph
Novamente’s “Atom Space”

- **Not a neural net**
  - No activation values, no attempt at low-level brain modeling
- **Not a semantic net**
  - Atoms may represent percepts, procedures, or parts of concepts
  - Most Nodes do not correspond to any simple English label
<table>
<thead>
<tr>
<th>Node Variety</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Perceptual Nodes</strong></td>
<td>These correspond to perceived items, like WordInstanceNode, CharacterInstanceNode, NumberInstanceNode, PixelInstanceNode</td>
</tr>
<tr>
<td><strong>Procedure Nodes</strong></td>
<td>These contain small programs called “schema,” and are called SchemaNodes. Action Nodes that carry out logical evaluations are called PredicateNodes.</td>
</tr>
<tr>
<td><strong>ConceptNodes</strong></td>
<td>This is a “generic Node” used for two purposes. An individual ConceptNode may represent a category of Nodes. Or, a Map of ConceptNodes may represent a concept.</td>
</tr>
<tr>
<td><strong>Psyche Nodes</strong></td>
<td>These areGoalNodes and FeelingNodes, which are special PredicateNodes that play a special role in overall system control, in terms of monitoring system health, and orienting overall system behavior.</td>
</tr>
<tr>
<td>Link Variety</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Logical links</strong></td>
<td>These represent symmetric or asymmetric logical relationships, either among Nodes (InheritanceLink, SimilarityLink), or among links and PredicateNodes (e.g. ImplicationLink, EquivalenceLink).</td>
</tr>
<tr>
<td><strong>MemberLink</strong></td>
<td>These denote fuzzy set membership.</td>
</tr>
<tr>
<td><strong>Associative links</strong></td>
<td>These denote generic relatedness, including HebbianLink learned via Hebbian learning, and a simple AssociativeLink representing relationships derived from natural language or from databases.</td>
</tr>
<tr>
<td><strong>ExecutionOutput Link</strong></td>
<td>These indicate input-output relationships among SchemaNodes and PredicateNodes and their arguments.</td>
</tr>
<tr>
<td><strong>Action-Concept links</strong></td>
<td>Called ExecutionLinks and EvaluationLinks, these form a conceptual record of the actions taken by SchemaNodes or PredicateNodes.</td>
</tr>
<tr>
<td><strong>ListLink and concatListLink</strong></td>
<td>These represent internally-created or externally-observed lists, respectively.</td>
</tr>
</tbody>
</table>
Links may denote generic association …
…or precisely specified relationships
## Attention Values

<table>
<thead>
<tr>
<th>Low Long-term Importance</th>
<th>High Long-term Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Useless</td>
<td>Remembered but not currently used (e.g. mother’s phone #)</td>
</tr>
<tr>
<td>Used then forgotten (e.g. most precepts)</td>
<td>Used and remembered</td>
</tr>
</tbody>
</table>
# Truth Values

<table>
<thead>
<tr>
<th>Weight of evidence low</th>
<th>Strength low</th>
<th>Strength high</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weakly suspected to be false</td>
<td>Weakly suspected to be true</td>
</tr>
<tr>
<td></td>
<td>Firmly known to be false</td>
<td>Firmly known to be true</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Weight of evidence high</th>
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<td>Firmly known to be true</td>
</tr>
</tbody>
</table>
Software Architecture
<table>
<thead>
<tr>
<th>MindAgent</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spontaneous Inference</strong></td>
<td>Uses PLN inference to infer new links from existing ones, driven by a general “fitness function” that aims to create surprising or useful information</td>
</tr>
<tr>
<td><strong>Goal-Directed Inference</strong></td>
<td>Uses PLN inference to figure out how to achieve current goals</td>
</tr>
<tr>
<td><strong>Goal Refinement</strong></td>
<td>Uses PLN inference and heuristics to create new goals refining existing ones</td>
</tr>
<tr>
<td><strong>Predicate Schematization</strong></td>
<td>Transforms logical knowledge regarding goal achievement into schemata that can be executed to achieve goals</td>
</tr>
<tr>
<td><strong>LogicalLinkMining</strong></td>
<td>Creates logical links out of nonlogical links (a form of pattern recognition)</td>
</tr>
<tr>
<td><strong>Evolutionary Predicate Learning</strong></td>
<td>Creates PredicateNodes containing predicates that predict membership in ConceptNodes</td>
</tr>
<tr>
<td><strong>Clustering</strong></td>
<td>Creates ConceptNodes representing clusters of existing ConceptNodes</td>
</tr>
<tr>
<td><strong>Importance Updating</strong></td>
<td>Updates Atom “importance” variables and other related quantities</td>
</tr>
<tr>
<td><strong>Hebbian Association Formation</strong></td>
<td>Builds and modifies HebbianLinks between Atoms, based on a PLN-derived Hebbian reinforcement learning rule</td>
</tr>
<tr>
<td><strong>Evolutionary Schema Learning</strong></td>
<td>Creates SchemaNodes that fulfill criteria, e.g. that are expected to satisfy given GoalNodes</td>
</tr>
<tr>
<td><strong>Concept Formation</strong></td>
<td>Creates speculative, potentially interesting new ConceptNodes via blending existing ones</td>
</tr>
<tr>
<td>MindAgent</td>
<td>Function</td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Predicate/Schema Formation</td>
<td>Creates speculative, potentially interesting new SchemaNodes and PredicateNodes by blending existing ones</td>
</tr>
<tr>
<td>Schema Execution</td>
<td>Enacts active SchemaNodes, allowing the system to carry out coordinated trains of action</td>
</tr>
<tr>
<td>Map Encapsulation</td>
<td>Scans the AtomTable for patterns and creates new Atoms embodying these patterns</td>
</tr>
<tr>
<td>Map Expansion</td>
<td>Takes schemata and predicates embodied in nodes, and expands them into multiple Nodes and links in the AtomTable (thus transforming complex Atoms into Maps of simple Atoms)</td>
</tr>
<tr>
<td>Homeostatic Parameter Adaptation</td>
<td>Applies evolutionary programming to adaptively tune the parameters of the system</td>
</tr>
</tbody>
</table>
Novamente Architecture

System Controller
relates to all components and controls resource allocation

Text I/O

Language Processor
active memory containing only language-pertinent Atoms

Global Attentional Focus
active memory containing only high-importance Atoms

Goal/Feeling Refinement
Inference

Central Active Memory
goals, feelings, cognitive schemata, declarative knowledge, inference and attention allocation

Intensive Pattern Mining
Evolution and Inference

Interaction Channel
Attentional Focus
active memory containing high-importance Atoms relative to the interaction channel

Sensorial Processing
sensations, patterns, perceptual schemata, attention allocation

Actuator Control
action schemata, attention allocation

Mind DB
RAM and disk Atom storage, controlling cashing in and out of RAM

FPGA-based Hardware
providing accelerated evolutionary learning (Prof. de Garis)

Large-Scale Pattern Mining
greedy data mining

Schema Learning
Evolution and Inference

Sensors

Actuators

AGI-SIM
Artificial Simulation Environment

Schema Learning Controller
determines replacement of control schemata
Feelings

Goals

Execution Management

Action Schemata

Percepts

Active Memory

World
Learning Dynamics
Engineering General Intelligence:

Contents

1. Patterns, Hypergraphs and General Intelligence
2. Atoms and Atomspaces
3. Denoting Atoms
4. Combo Trees and the Combo Language
5. The Mind OS
6. Embodied Goal-Oriented Cognition
7. Procedure Execution
8. Dimensional Embedding
9. Evolutionary Procedure Learning
10. Speculative Concept Formation
11. Integrative Procedure and Predicate Learning
12. Attention Allocation
13. Map Encapsulation and Expansion
Probabilistic Logic Networks:

Contents
(with Matt Ikle', Izabela Freire Goertzel, Ari Heljakka)

1. Introduction
2. Knowledge Representation
3. Experiential Semantics
4. First-Order Extensional Inference: Rules and Strength Formulas
5. Specialized Approaches for Large-Scale Inference
6. The Inference Metric
7. Error Magnification in Inference Formulas
8. Inference with Distributional Truth Values
9. Higher-Order Extensional Inference: Rules and Strength Formulas
10. Intensional Inference
11. Weight of Evidence
12. Temporal and Causal Inference
13. Applying Probabilistic Logic Networks
Novamente contains multiple heuristics for Atom creation, including "blending" of existing Atoms.
Example PLN Rules Acting on ExtensionalInheritanceLinks
Unification:

\[
\text{Imp } <1.00, 0.95> \\
\text{AND} \\
\text{Inh}(t, \text{toy}) \\
\text{Inh}(b, \text{bucket}) \\
\text{Eval placed}(_{\text{under}})(t, b) \\
\text{Eval found}(_{\text{under}})(t, b) \\
\text{Inh}(\text{toy}_6, \text{toy}) \\
\text{Inh}(\text{red\_bucket}_6, \text{bucket}) \\
\text{Eval placed}(_{\text{under}})(\text{toy}_6, \text{red\_bucket}_6) \\
\text{AND } <1.00, 0.98> \\
\text{Inh}(\text{toy}_6, \text{toy}) \\
\text{Inh}(\text{red\_bucket}_6, \text{bucket}) \\
\text{Eval placed}(_{\text{under}})(\text{toy}_6, \text{red\_bucket}_6) \\
\]

\[\|-\]

\[
\text{Imp } <1.00, 0.95> \\
\text{AND } <1.00, 0.98> \\
\text{Inh}(\text{toy}_6, \text{toy}) \\
\text{Inh}(\text{red\_bucket}_6, \text{bucket}) \\
\text{Eval placed}(_{\text{under}})(\text{toy}_6, \text{red\_bucket}_6) \\
\text{Eval found}(_{\text{under}})(\text{toy}_6, \text{red\_bucket}_6) \\
\]

Higher-order PLN inference handles complex inferences with variables, quantifiers, etc.
Atoms associated in a dynamic “map” may be grouped to form new Atoms: the Atomspace hence explicitly representing patterns in itself.
Grounding of natural language constructs is provided via inferential integration of data gathered from linguistic and perceptual inputs.
Attention Allocation

MindAgents

System Activity Table

Guides inference control, etc.

Atom Table

Pattern Mining

Adjusts attention values, makes Hebbian Links
Novamente:
The Current Reality
Implemented Components

- **Novamente core system**
  - AtomTable, MindAgents, Scheduler, etc.
  - Now runs on one machine; designed for distributed processing
- **PLN**
  - Relatively crude inference control heuristics
  - Simplistic predicate schematization
- **MOSES**
  - Little experimentation has been done evolving procedures with complex control structures
- **Schema execution framework**
  - Enacts learned procedures
- **AGISim**
  - And proxy for communication with NM core
- **NLP front end**
  - External NLP system for “cheating” style knowledge ingestion
Current AGISim Learning Architecture

AGISim

Schema Execution

MOSES Evolutionary Learning

Central Memory (Main Atom Table)

actions

predicate schematization

inferential fitness evaluation

...goals, knowledge

...goals, knowledge

perceptions
Simple, Initial AGISim Experiments

- Fetch
- Tag
- Piagetan A-not-B experiment
- Word-object association
Notice novelty
Gather knowledge
Create and consolidate abstract knowledge

Log:
Teacher: Where is the toy?
Teacher: Open it
Teacher: Good! The toy is there!
Inference Trajectory for A-not-B

Target:
Eval found_under(toy_6,$1)

Step 1
ANDRule:
  Inh (toy_6,toy)
  Inh (red_bucket_6,bucket)
  Eval placed_under(toy_6,red_bucket_6)

|-
AND <1.00, 0.98>
  Inh (toy_6,toy)
  Inh (red_bucket_6,bucket)
  Eval placed_under(toy_6,red_bucket_6)

Step 2
Unification:

Imp <1.00, 0.95>
  AND
  Inh($t,toy)
  Inh($b,bucket)
  Eval placed_under($t,$b)
  Eval found_under($t,$b)

AND
  Inh (toy_6,toy)
  Inh (red_bucket_6,bucket)
  Eval placed_under(toy_6,red_bucket_6)

|-
Imp <1.00, 0.94>
  AND
  Inh (toy_6,toy)
  Inh (red_bucket_6,bucket)
  Eval placed_under(toy_6,red_bucket_6)

Step 3
Modus Ponens

Imp <1.00, 0.94>
  AND
  Inh (toy_6,toy)
  Inh (red_bucket_6,bucket)
  Eval placed_under(toy_6,red_bucket_6)
  Eval found_under(toy_6, red_bucket_6)

AND <1.00, 0.98>
  Inh (toy_6,toy)
  Inh (red_bucket_6,bucket)
  Eval placed_under(toy_6,red_bucket_6)

|-
Eval found_under(toy_6, red_bucket_6) <1.00, 0.93>
Predicate Schematization

Logical knowledge

EvPredImp <0.95, 0.3>
   Execution try(goto box)
   Eval near box

SimultaneousImplication
   Eval near box
   Eval can_do(push box)

EvPredImp <0.6,0.4>
   And
      Eval can_do(push box)
      Execution try(push box)
   Evaluation Reward

Executable procedure

repeat
goto box
near box
repeat
push box
Reward
NLP Subsystem

• RelEx (Relationship Extractor)
  – Developed under subcontract to INSCOM
  – Based on Carnegie-Mellon link parser
  – Add hand-crafted semantic mapping rules
  – Add statistical methods for disambiguation and reference resolution
  – Designed to allow easy feeding of NL knowledge into Novamente
  – Can be modified to enable simple language generation

• INLINK
  – Interactive system for NL knowledge entry
  – Allows user to correct RelEx’s mistakes prior to submission of knowledge into Novamente
NLP Subsystem

Viewed as “scaffolding” from an AGI perspective

Using it, we may feed Novamente semantic information that will help guide its experiential, embodied language learning process
Mugniyeh is a senior member of Hizbullah.
He is one of the founders of Hizbullah.
He is the head of security for Hizbullah.
The members of Hizbullah are Shiite Muslims.
He was responsible for the bombing of the U.S. embassy in Beirut in 1983.
63 people died in the bombing of the U.S. embassy in Beirut in 1983.
He was also responsible for the truck bombing of the U.S. Marine barracks in Beirut in 1983.

Sentence:
He was also responsible for the truck bombing of the U.S. Marine barracks in Beirut in 1983.

Sub/Categorization Frames:

subj-DESCRIPTOR
also = [ responsible also ]

subjAGENT
responsible = [ he responsible bombing ]

subj-FOCUS
truck = [ bombing truck ]

bombling = [ bombing 1983 barrack ]

U.S._Marine = [ barrack U.S._Marine ]

barrack = [ barrack Beirut ]
Mughrabi is a senior member of Hezbollah. He is one of the founders of Hezbollah. He is the head of security for Hezbollah. The members of Hezbollah are Shiite Muslims. He was responsible for the bombing of the U.S. embassy in Beirut in 1983. 63 people died in the bombing of the U.S. embassy in Beirut in 1983. He was also responsible for the truck bombing of the U.S. Marine barracks in Beirut in 1983.

Sentence: He was also responsible for the truck bombing of the U.S. Marine barracks in Beirut in 1983.

Disambiguated SARs (Syntactic Argument Relations):
- subj-n (truck, bombing)
- subj-r (also, responsible)

Below, you can select the correct sense for each word or SAR:

- he: Male pronoun [he]: Refers to a male.
- also: well, besides, too, also, likewise: In addition: "he has a Mercedes, too"
- responsible: responsible, responsible_for(p): being the agent or cause: "determined who was the responsible party"; "terrorists were responsible for the damage"
- for: FOCUS: For all his large size, he moves gracefully. (in spite of)
- truck: FOCUS: For all his large size, he moves gracefully. (in spite of)
He was also responsible for the truck bombing of the U.S. Marine barracks in Beirut in 1983.
he was also responsible for the truck bombing of the U.S. Marine barracks in Beirut in 1983.
Novamente:
The Path Ahead
Hypothetical Timeline

2006-2007:
– Complete “infantile” stage behaviors in AGISim
– Initial integration of existing NLP system

2007-2019:
– Enter concrete-operational stage
– Integration of NLP code with learning mechanisms
  – Implement distributed processing infrastructure

2008-2012:
– Powerful natural-language question-answering
– Focus on embodied language learning

2009-2014:
– Formal stage?
  – Integration of Mizar DB?
Credits

Novamente:
• Cassio Pennachin
• Moshe Looks
• Ari Heljakka
• Andre Senna
• Izabela Freire Goertzel
• Welter Silva
• Michael Ross
• Hugo Pinto

AGISim:
• Ari Heljakka
• Welter Silva