LOGIC & SEMANTIC TECHNOLOGIES FOR COMPUTER SCIENCE EDUCATION

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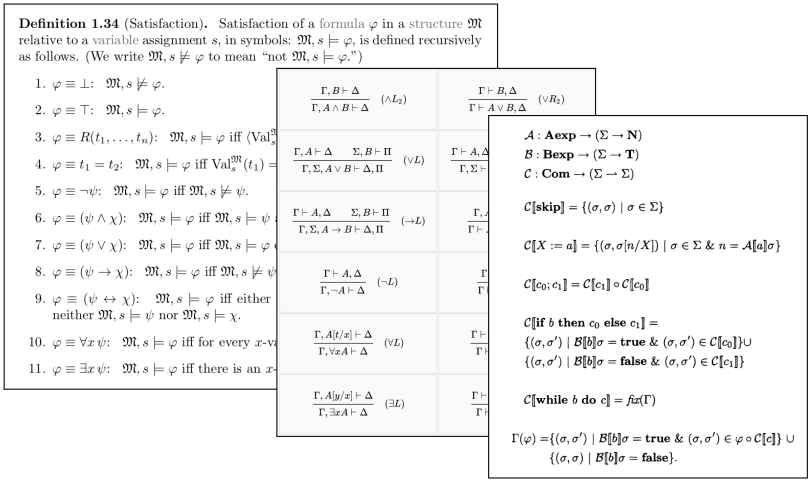
Logic and Semantics in Education



Definition 1.34 (Satisfaction). Satisfaction of a formula φ in a structure $\mathfrak{M}$ relative to a variable assignment s, in symbols: $\mathfrak{M}, s \models \varphi$, is defined recursively as follows. (We write $\mathfrak{M}, s \not\models \varphi$ to mean "not $\mathfrak{M}, s \models \varphi$.")

1. $\varphi \equiv \bot$: $\mathfrak{M}, s \not\models \varphi$.
2. $\varphi \equiv \top$: $\mathfrak{M}, s \models \varphi$.
3. $\varphi \equiv R(t_1, \ldots, t_n)$: $\mathfrak{M}, s \models \varphi$ iff $\langle \mathrm{Val}_s^{\mathfrak{M}}$
4. $\varphi \equiv t_1 = t_2$: $\mathfrak{M}, s \models \varphi$ iff $\mathrm{Val}_s^{\mathfrak{M}}(t_1) =$
5. $\varphi \equiv \neg\psi$: $\mathfrak{M}, s \models \varphi$ iff $\mathfrak{M}, s \not\models \psi$.
6. $\varphi \equiv (\psi \wedge \chi)$: $\mathfrak{M}, s \models \varphi$ iff $\mathfrak{M}, s \models \psi$
7. $\varphi \equiv (\psi \vee \chi)$: $\mathfrak{M}, s \models \varphi$ iff $\mathfrak{M}, s \models \varphi$
8. $\varphi \equiv (\psi \to \chi)$: $\mathfrak{M}, s \models \varphi$ iff $\mathfrak{M}, s \not\models \psi$
9. $\varphi \equiv (\psi \leftrightarrow \chi)$: $\mathfrak{M}, s \models \varphi$ iff either neither $\mathfrak{M}, s \models \psi$ nor $\mathfrak{M}, s \models \chi$.
10. $\varphi \equiv \forall x\, \psi$: $\mathfrak{M}, s \models \varphi$ iff for every x-va
11. $\varphi \equiv \exists x\, \psi$: $\mathfrak{M}, s \models \varphi$ iff there is an x-

$$\frac{\Gamma, B \vdash \Delta}{\Gamma, A \wedge B \vdash \Delta}\ (\wedge L_2) \qquad \frac{\Gamma \vdash B, \Delta}{\Gamma \vdash A \vee B, \Delta}\ (\vee R_2)$$

$$\frac{\Gamma, A \vdash \Delta \qquad \Sigma, B \vdash \Pi}{\Gamma, \Sigma, A \vee B \vdash \Delta, \Pi}\ (\vee L) \qquad \frac{\Gamma \vdash A, \Delta}{\Gamma, \Sigma \vdash}$$

$$\frac{\Gamma \vdash A, \Delta \qquad \Sigma, B \vdash \Pi}{\Gamma, \Sigma, A \to B \vdash \Delta, \Pi}\ (\to L) \qquad \frac{\Gamma, A}{\Gamma \vdash}$$

$$\frac{\Gamma \vdash A, \Delta}{\Gamma, \neg A \vdash \Delta}\ (\neg L) \qquad \frac{\Gamma}{\Gamma}$$

$$\frac{\Gamma, A[t/x] \vdash \Delta}{\Gamma, \forall x A \vdash \Delta}\ (\forall L) \qquad \frac{\Gamma \vdash}{\Gamma}$$

$$\frac{\Gamma, A[y/x] \vdash \Delta}{\Gamma, \exists x A \vdash \Delta}\ (\exists L) \qquad \frac{\Gamma \vdash}{\Gamma}$$

$\mathcal{A} : \mathbf{Aexp} \to (\Sigma \to \mathbf{N})$
$\mathcal{B} : \mathbf{Bexp} \to (\Sigma \to \mathbf{T})$
$\mathcal{C} : \mathbf{Com} \to (\Sigma \to \Sigma)$

$\mathcal{C}[\![\mathbf{skip}]\!] = \{(\sigma, \sigma) \mid \sigma \in \Sigma\}$

$\mathcal{C}[\![X := a]\!] = \{(\sigma, \sigma[n/X]) \mid \sigma \in \Sigma \ \&\ n = \mathcal{A}[\![a]\!]\sigma\}$

$\mathcal{C}[\![c_0; c_1]\!] = \mathcal{C}[\![c_1]\!] \circ \mathcal{C}[\![c_0]\!]$

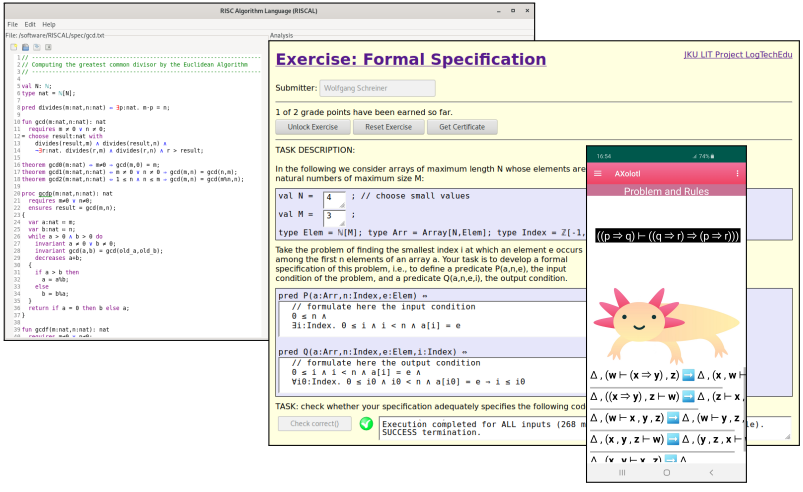
$\mathcal{C}[\![\mathbf{if}\ b\ \mathbf{then}\ c_0\ \mathbf{else}\ c_1]\!] =$
$\{(\sigma, \sigma') \mid \mathcal{B}[\![b]\!]\sigma = \mathbf{true}\ \&\ (\sigma, \sigma') \in \mathcal{C}[\![c_0]\!]\} \cup$
$\{(\sigma, \sigma') \mid \mathcal{B}[\![b]\!]\sigma = \mathbf{false}\ \&\ (\sigma, \sigma') \in \mathcal{C}[\![c_1]\!]\}$

$\mathcal{C}[\![\mathbf{while}\ b\ \mathbf{do}\ c]\!] = \mathit{fix}(\Gamma)$

$\Gamma(\varphi) = \{(\sigma, \sigma') \mid \mathcal{B}[\![b]\!]\sigma = \mathbf{true}\ \&\ (\sigma, \sigma') \in \varphi \circ \mathcal{C}[\![c]\!]\} \cup$
$\{(\sigma, \sigma) \mid \mathcal{B}[\![b]\!]\sigma = \mathbf{false}\}.$

Typically still presented as "paper and pencil" topics.

Logic and Semantics in Education



But today the educational process can be substantially supported by *software*.

Projects LOGTECHEDU and SemTech

- LOGTECHEDU: Logic Technologies for Computer Science Education.
  - JKU LIT (Linz Institute of Technology), 2018–2020.
  - Institutes FMV (Biere, Cerna, Seidl) and RISC (Schreiner, Windsteiger).
  - `http://fmv.jku.at/logtechedu`
- SemTech: Semantic Technologies for Computer Science Education.
  - Austrian OEAD WTZ and Slovak SRDA, 2018–2019.
  - JKU Linz (Schreiner) and TU Kosice (Novitzká, Steingartner).
  - `https://www.risc.jku.at/projects/SemTech`

Investigate the potential of logic&semantics-based software for education.

Educating with the Help of Logic&Semantics

- Today much of logic&semantics can be automated by computer software.
  - Substantial advances in computational logic (automated reasoning, model checking, satisfiability solving).
- By the application of such software education may be supported.
  - May demonstrate the practical usefulness of logic&semantics.
  - May increase the motivation of students to model and to reason.
- The ultimate goal is logic&semantics-based self-directed learning.
  - Teachers become “enablers” by providing basic knowledge and skills.
  - Students “educate themselves” by solving problems.
    - (Voluntary) quizzes, (mandatory) assignments, possibly (graded) exams.

Core idea: let students actively engage with lecturing material by solving concrete problems and by receiving immediate feedback from the software.

Research Strands

- Solver Guided Exercises (Limboole, Boolector)
- Teaching Solver Technology (Limboole, Boolector)
- Proof Assistants for Education (Theorema, AXolotl)
- Specification and Verification Systems for Education (RISCAL)
- Formal Semantics of Programming Languages ($\mathscr{J}ane$)
- Logic across the Subjects in Primary, Secondary and Higher Education

Various aspects of the general idea.

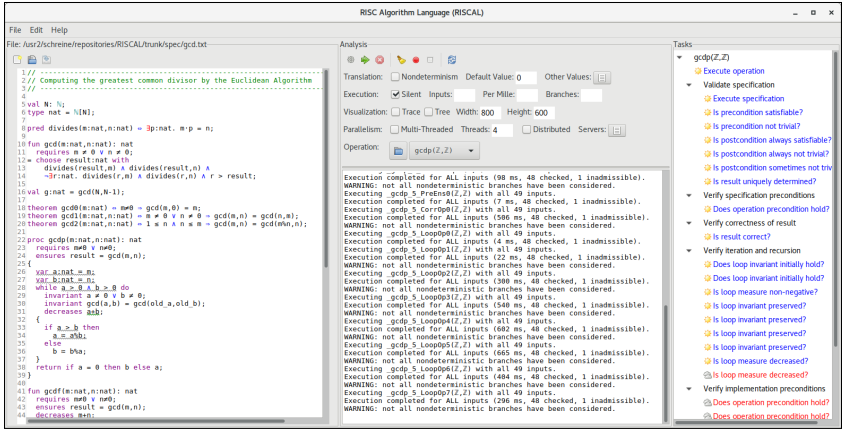
The RISC Algorithm Language (RISCAL)

A language and software system for investigating finite mathematical models (i.e., a “mathematical model checker”).

- Formulation of mathematical theories and theorems.
- Formulation and specification of (also non-deterministic) algorithms.
- Rooted in strongly typed first order logic and set theory.
- All types are finite (with sizes determined by model parameters).
- All formulas are automatically decidable (by evaluating their semantics).
- Correctness of all algorithms is decidable (by evaluating their semantics).
- Automatic generation of (again decidable) verification conditions.

Checking in some model of fixed size *before* proving in models of arbitrary size.

The RISCAL Software



https://www.risc.jku.at/research/formal/software/RISCAL

RISCAL Theories and Theorems

```
val N: ℕ;
type Literal = ℤ[-N,N];
type Clause  = Set[Literal];
type Formula = Set[Clause];
type Valuation  = Set[Literal];

pred satisfies(v:Valuation, l:Literal) ⇔ l∈v;
pred satisfies(v:Valuation, c:Clause) ⇔ ∃l∈c. satisfies(v, l);
pred satisfies(v:Valuation, f:Formula) ⇔ ∀c∈f. satisfies(v,c);
pred satisfiable(f:Formula) ⇔ ∃v:Valuation. satisfies(v,f);
pred valid(f:Formula) ⇔ ∀v:Valuation. satisfies(v,f);
fun not(f: Formula):Formula = { c | c:Clause with ∀d∈f. ∃l∈d. -l∈c };
...
theorem notValid(f:Formula)
  requires formula(f);
⇔ valid(f) ⇔ ¬satisfiable(not(f));
```

First-order logic, integers, tuples/records, arrays/maps, sets, algebraic types.

RISCAL Algorithms

```
multiple pred DPLL(f:Formula)
  requires formula(f);
  ensures result ⇔ satisfiable(f);
  decreases |literals(f)|;
⇔ if f = ∅[Clause] then
    ⊤
  else if ∅[Literal] ∈ f then
    ⊥
  else choose l∈literals(f) in
    DPLL(substitute(f,l)) ∨
    DPLL(substitute(f,-l));
```

```
proc DPLL2(f:Formula): Bool
  requires ...; ensures ...;
{
  var stack: Array[n+1,Formula] :=
    Array[n+1,Formula](∅[Clause]);
  ...
  while ¬satisfiable ∧ number>0 do
    ...
    invariant satisfiable(f) ⇔ ...;
    decreases if satisfiable then 0 else
      ∑k:ℕ[n] with k<number. size(stack[k]);
  {
    ...
    choose l∈literals(g);
    ...
  }
  return satisfiable;
}
```

Functions, procedures, recursion, nondeterminism.

RISCAL Systems

```
proc system(s0:State): Tuple[N[N],Array[N,State]]
  requires init(s0);
{
  var s:State = s0;
  var i:N[N] = 0;
  var t:Array[N,State] = Array[N,Action](s);
  while ¬goal(s) ∧ i < N do
  {
    choose s1:State with next(s,s1);
    s = s1; i = i+1; t[i] = s;
  }
  return hi,ti;
}
```

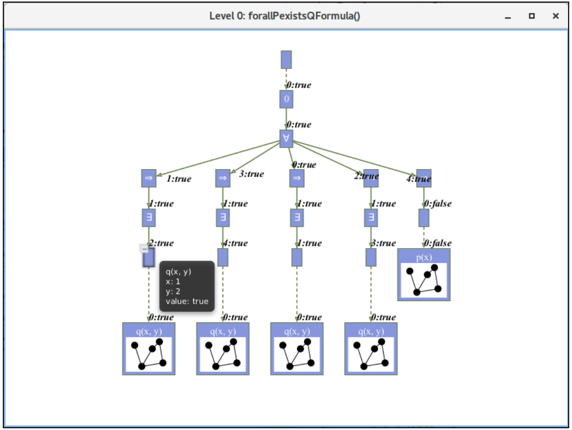
Modeling and analysis of nondeterministic transition systems described by their initial state condition and next state relation.

RISCAL Checking

```
Using N=2.
Type checking and translation completed.
...

Executing notValid(Set[Set[ℤ]]) with selected 512 inputs.
Execution completed for SELECTED inputs (111 ms, 512 checked, 0 inadmissible).

Executing DPLL(Set[Set[ℤ]]) with selected 512 inputs.
Execution completed for SELECTED inputs (1219 ms, 512 checked, 0 inadmissible).

Executing DPLL2(Set[Set[ℤ]]) with selected 512 inputs.
435 inputs (435 checked, 0 inadmissible, 0 ignored)...
Execution completed for SELECTED inputs (2436 ms, 512 checked, 0 inadmissible).

Executing DPLL_OutputCorrect(Set[Set[ℤ]]) with selected 512 inputs.
Execution completed for SELECTED inputs (609 ms, 512 checked, 0 inadmissible).
```

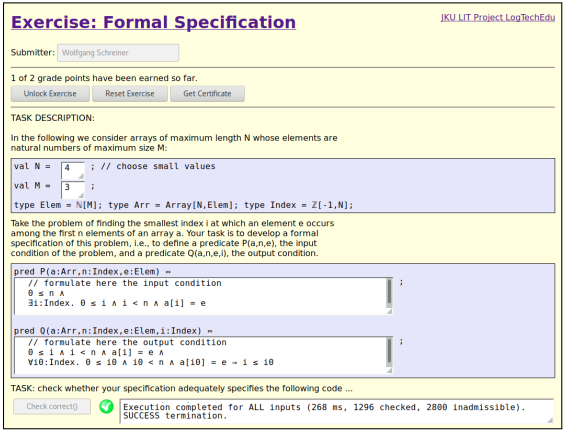
Automatic checking of theorems, algorithms, generated verification conditions.

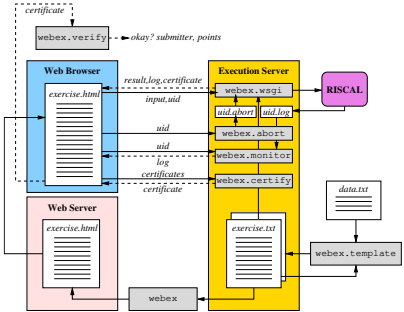
RISCAL Visualization



Pruned evaluation trees to explain the truth value of a formula.

RISCAL Web Exercises

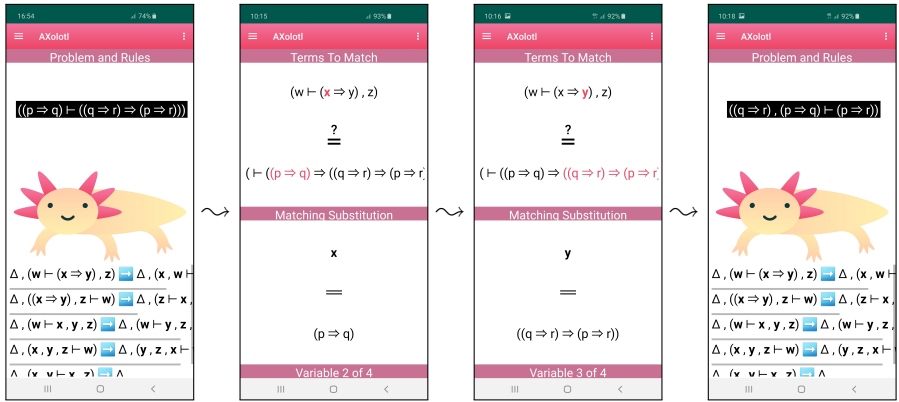




Framework for web-based exercises checked by a RISCAL server.

AXolotl

Author: David Cerna; Google Play Store (search for “AXolotl Logic Software”)



Proving on a smartphone by a purely touch-based interface (no keyboard input).

Educational Usage

- "Formal Methods in Software Development" (JKU, master programs "Computer Science" and "Computer Mathematics")
  - RISCAL: formal problem specifications; specification and verification of imperative programs.
- "Formal Methods and Specification" (TU Prague, Stefan Ratschan, master program "Informatics")
  - RISCAL: formal specification and verification of imperative programs.
- "Formal Modeling" (JKU, bachelor program "Technical Mathematics")
  - RISCAL: formal modeling of computational problems, search and scheduling problems ("puzzles"), dynamic systems.
- "Logic" (JKU, bachelor prog. "Computer Science" and "Artificial Intelligence")
  - RISCAL, AXolotol, Theorema, Limboole, Boolector, Z3.
  - Bonus (RISCAL Web) and laboratory exercises (RISCAL desktop, AXolotol).
- Bachelor and Master Theses

RISCAL Experience

Observations, results of questionnaires, test/exam results.

- Students with some technical/formal background (2nd year and higher):
  - High satisfaction with ease of use.
  - Much more liked than “proof-based” logic software.
  - Many students were indeed enabled to independently develop adequate formal specifications, models, program annotations.
- Absolute beginners (1. sem. 2018, RISCAL web interface not yet available):
  - More used than other tools on FO and SMT (but less than SAT solvers).
  - Those who performed the exercises scored better in tests.
  - Students that scored poorly in tests did not use the software.
  - “Extrinsic motivation”: mainly used to get additional grade points.

From a certain background/level on, substantial increase in motivation and interest (but not a statistically significant effect on grades).

Conclusions and Further Work

- Logic&semantics software can indeed be a factor to increase interest in "formal" topics and foster "self-directed" learning.
- However, students mainly profit if they already have certain abilities respectively some background.
- Care has to be taken to not "loose" the weaker beginners; these are easily overwhelmed by information overload or (trivial) syntactic/technical difficulties.
- We are currently running a beginner's course with an easier to use web-based interface and will evaluate the difference it makes.
- Future work will concentrate on development of software-based course materials and on technical extensions (integration with SMT solvers and interactive provers, modeling and reasoning about concurrency).

https://www.risc.jku.at/research/formal/software/RISCAL