CUTECat

Concolic Execution for Computational Law

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Introduction

Computational law

- **Computational laws** encode algorithms: taxes, social benefits, etc.
- Administrations implement them as programs
- Critical: *e.g.* French military payroll system Louvois: 120k military personnel over- or under-paid, overpayments totalling 545M € to pay back

Structure of computational law: income tax example

Article 1

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Article 3

If the income is less than $10,000, the percentage mentioned at article 1 is 10%.

Article 4

For people in charge of 3 or more children, the percentage mentioned at article 1 is 15%.

Structure of computational law: income tax example

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Article 3 exception

If the income is less than $10,000, the percentage mentioned at article 1 is 10%.

Article 4 exception

For people in charge of 3 or more children, the percentage mentioned at article 1 is 15%.

Default logic

The Catala domain-specific language

~~~
# Article 1
The income tax is a fixed percentage of
the income.
```catala

scope IncomeTaxComputation:
 definition income_tax equals
   house.income * tax_rate
```

# Article 2
The fixed percentage mentioned at
article 1 is 20%.
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scope IncomeTaxComputation:
  definition tax_rate equals 20%
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~~~

~~~
# Article 3
If the income is less than $10,000, the
percentage mentioned at article 1 is 10%.
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scope IncomeTaxComputation:
 exception definition tax_rate
  under condition house.income <= $10,000
  consequence equals 10%
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# Article 4
For people in charge of 3 or more
children, the percentage mentioned at
article 1 is 15%.
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scope IncomeTaxComputation:
 exception definition tax_rate
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- Literate programming

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- Literate programming
- Follows the exception/default structure of the law

Kinds of error

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  - unhandled cases
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  - resolved by lawyer/court if implementation is correct

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- **Ambiguities** in the code
    - interpretation conflicts, *e.g.* `income = $9,000` and `children = 4`
    - unhandled cases
    - in Catala: ambiguity = runtime error
    - resolved by lawyer/court if implementation is correct
- Other errors: division by zero, assertion error, etc.

Finding errors

What properties do we want in our search for errors?

- Find errors automatically
- Systematically:
  - find complex corner cases
  - complete coverage
- Handle default logic
- Generate (counter-)examples for non-expert users

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- Avoid some common obstacles for free:
  - no loops or memory
  - all programs terminate

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→ Symbolic execution

- Avoid some common obstacles for free:
  - no loops or memory
  - all programs terminate
- But some features are hard to encode symbolically

Outline

Concolic execution of default terms

Performance and usability improvements

Experimental evaluation

Concolic execution of default terms

Concolic execution: first example

Concolic = *concrete* + symb*olic*

```
if x > 0
  then 0
  else if y < 0
    then 1
    else error
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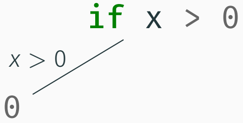

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1	1	20	0	$x > 0$	

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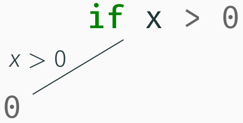

if x > 0

$x > 0$

0

Step	x	y	Output	Constraints after evaluation	Next path to try
1	1	20	0	$x > 0$	$\neg(x > 0)$

SMT

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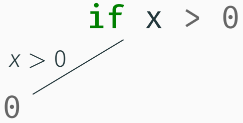

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⤸ SMT

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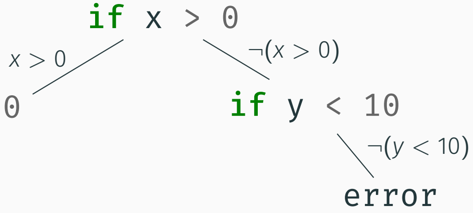

`if x > 0`

$x > 0$

`0`

$\neg(x > 0)$

`if y < 10`

$\neg(y < 10)$

`error`

Step	x	y	Output	Constraints after evaluation	Next path to try	
1	1	20	0	$x > 0$	$\neg(x > 0)$	⤸ SMT
2	0	20	`error`	$\neg(x > 0) \wedge \neg(y < 10)$	$\neg(x > 0) \wedge y < 10$	⤸ SMT

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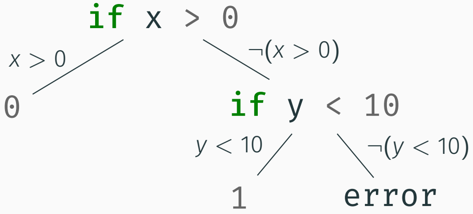

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1	1	20	0	$x > 0$	$\neg(x > 0)$
2	0	20	`error`	$\neg(x > 0) \land \neg(y < 10)$	$\neg(x > 0) \land y < 10$
3	0	9	1	$\neg(x > 0) \land y < 10$	-

SMT

SMT

Default terms: syntax

$$\text{Source code} \xrightarrow{\text{compiler}} \textbf{default terms}$$

$$e ::= \langle e_1 , \ldots , e_n \mid b_{default} :- e_{default} \rangle$$

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$$\begin{array}{lll} v & ::= & \texttt{true} \mid \texttt{false} \mid n \mid \ldots \\ & \mid & \varnothing \\ & \mid & \circledast \end{array}$$

Default terms: semantics

$$
\begin{array}{l}
\langle \\
\quad \langle \mid \texttt{income} \leq \$10,000 \ \texttt{:-}\ 10\% \rangle\texttt{,} \\
\quad \langle \mid \texttt{nb\_children} \geq 3 \ \texttt{:-}\ 15\% \rangle \\
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1. Evaluate all exceptions
2. If **exactly 1 exception** is raised, then **return its value**
3. Else if **at least 2 exceptions** are raised, then **return** $\circledast$
4. Else if **0 exceptions** are raised, evaluate $b_{default}$ and
    - If $b_{default} = \texttt{true}$, then **evaluate** $e_{default}$
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Concolic execution of default terms

$$\langle \langle \mid \texttt{income} \leq \$10,000 \;\texttt{:-}\; 10\% \rangle, \langle \mid \texttt{nb\_children} \geq 3 \;\texttt{:-}\; 15\% \rangle \mid \texttt{true} \;\texttt{:-}\; 20\% \rangle$$

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$\texttt{income}$ = \$9,000; $\texttt{nb\_children}$ = 4

$$\texttt{income} \leq \$10,000$$

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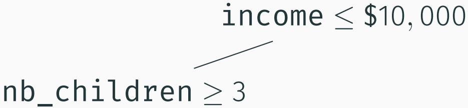

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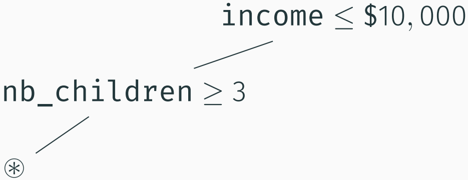

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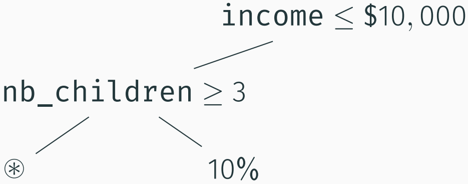

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10%

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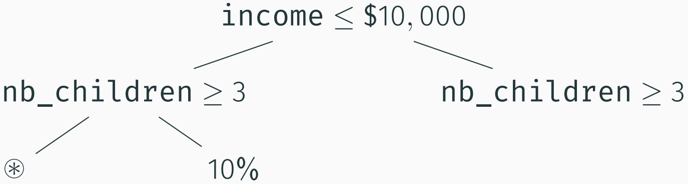
$\texttt{income} = \$11{,}000; \quad \texttt{nb\_children} = 4$



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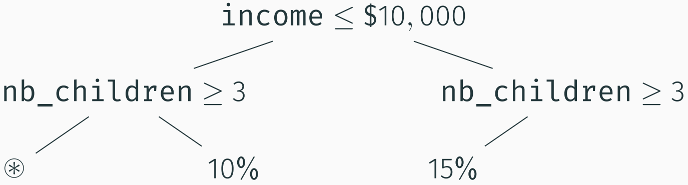

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Concolic execution of default terms

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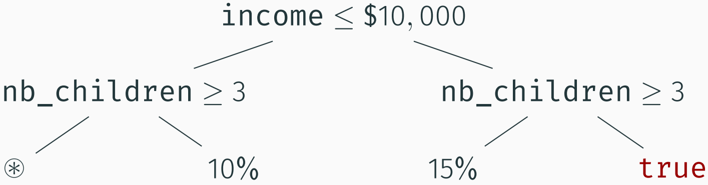

income ≤ $10, 000

nb_children ≥ 3

nb_children ≥ 3

⊛

10%

15%

true

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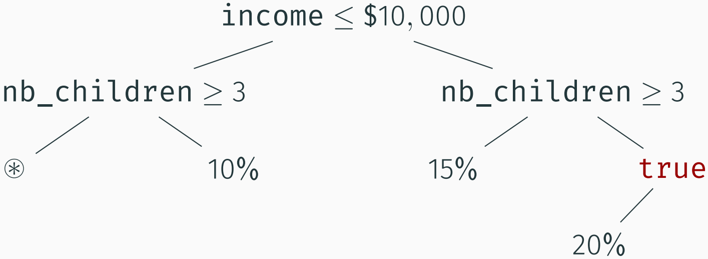

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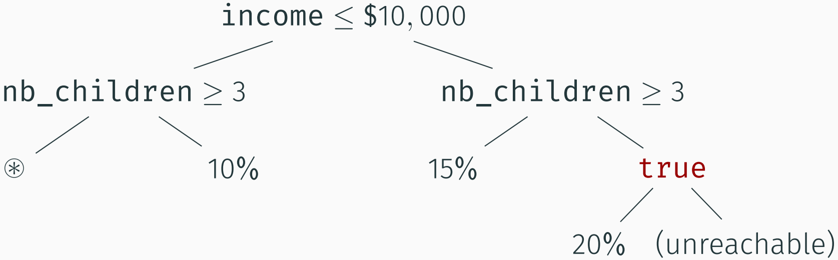
$\texttt{income}$ = ???; $\texttt{nb\_children}$ = ???



Fixing the interpretation conflict

Suppose the lawyer says the `income` condition has priority.

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Fixing the interpretation conflict

Suppose the lawyer says the `income` condition has priority.
→ it becomes an exception to the exception.

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Performance and usability improvements

Performance optimizations using reordering

Theorem (Independence of exception evaluation order)
If there is a default value v such that

$$\langle \dots, e_i, \dots, e_j, \dots \mid b_{default} :- e_{default} \rangle \longrightarrow^* v,$$

then

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Example:

$$\langle \dots, \circledast \mid b_{default} :- e_{default} \rangle \sim \langle \circledast, \dots \mid b_{default} :- e_{default} \rangle$$

Human-compatible test cases

~~~
# Article 3
If the income is less than $10,000, the percentage
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```catala
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Query: income > $10,000 ?

Human-compatible test cases

~~~
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If the income is less than $10,000, the percentage
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  under condition house.income <= $10,000
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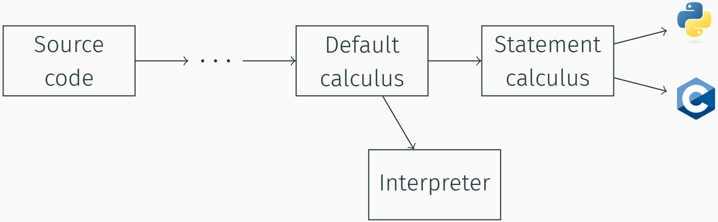
Query: income > $10,000 ? → Answer: ~~$10,000.01~~ **$11,000**

- Difficult for lawyers to compute by hand
- Find more usable input values using soft constraints
  - *e.g.* **round to $1,000**

Implementation of CUTECat



Source code

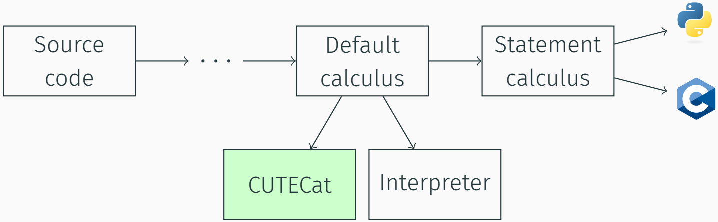
. . .

Default calculus

Statement calculus

Interpreter

Implementation of CUTECat



- Integrated into Catala compiler’s *default calculus* IR
- 3.4k lines of OCaml code
- Z3 SMT Solver

Experimental evaluation

Code base

Law	Lines of law in Markdown	Lines of Catala	Total
French housing benefits	5736	8615	14351

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French housing benefits	**5736**	**8615**	**14351**
US Tax code § 132	35	56	91
Minimum wage	74	161	235
Family quotient	36	165	201
Handwritten unit tests	139	699	838

Performance on small programs

	Time (s)		
Law	No optimizations	Optimized	Generated tests
US Tax code	0.27	0.02	10
Minimum wage	1.01	0.08	17
Family quotient	82.61	4.34	381

Case study: housing benefits

Key results

- 186,390 test cases generated in **7h of CPU time**
- 99.83% of tests satisfy soft constraints
- 366s spent in solver, the rest in evaluation
- 4.5x overhead w.r.t. Catala interpreter
- Able to find a conflict

Conclusion

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- Novel concolic semantics for default logic
- Integrated with Catala toolchain
- Optimizations improve efficiency and usability by lawyers
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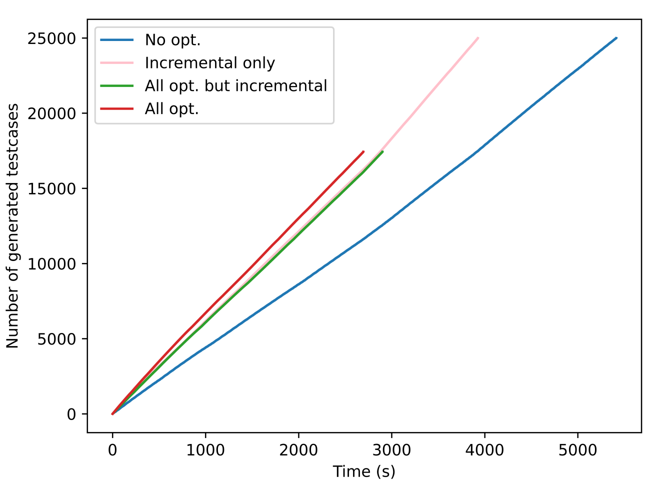
Ablation study



Generated tests vs time