CUTECat

Concolic Execution for Computational Law

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Introduction

Computational law

- **Computational laws** specify 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 2 — default case

The fixed percentage mentioned at article 1 is 20%.

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%.

```catala
scope IncomeTaxComputation:
  definition tax_rate equals 20%
```

- Literate programming

 # Article 3
If the income is less than $10,000, the percentage mentioned at article 1 is 10%.

```catala
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%.

```catala
scope IncomeTaxComputation:
 exception definition tax_rate
  under condition house.nb_children >= 3
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- Literate programming
- Follows the exception/default structure of the law

Kinds of error

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  - interpretation conflicts, *e.g.* `income = $9,000` and `children = 4`
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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 lawyers/administration 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-programmer users

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

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$\rightarrow$ 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 = *conc*rete + symb*olic*

```
if x > 0
    then 0
    else if y < 10
        then y
        else error
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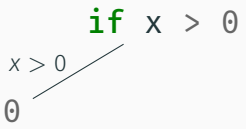

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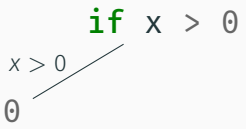

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↻ SMT

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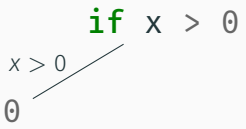

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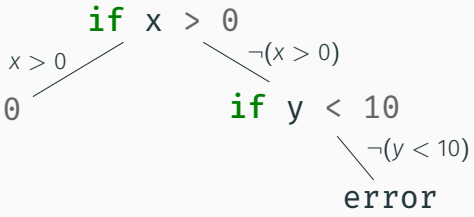

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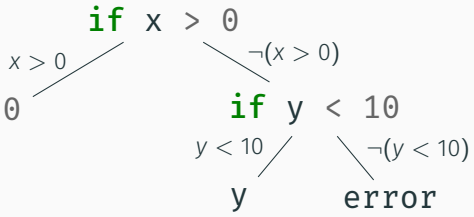

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3	0	9	9	$\neg(x > 0) \wedge y < 10$	-	

Default terms: syntax

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

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

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

Default terms: semantics

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  ⟨ | income ≤ $10,000 :- 10%⟩,
  ⟨ | nb_children ≥ 3 :- 15%⟩
  | true :- 20%
⟩
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1. Evaluate all exceptions
2. If **exactly 1 exception** is raised, then **return its value**
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4. Else if **0 exceptions** are raised, evaluate $b_{default}$ and
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Concolic execution of default terms

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`income` = $9,000; `nb_children` = 4

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

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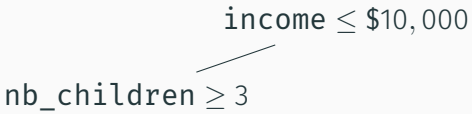

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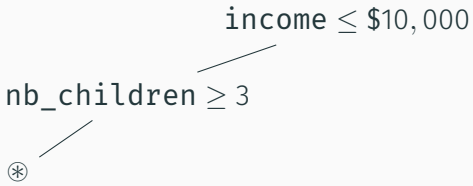

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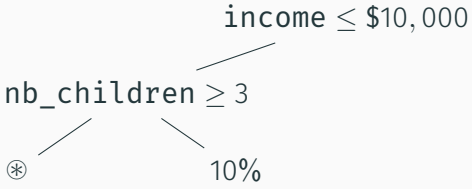

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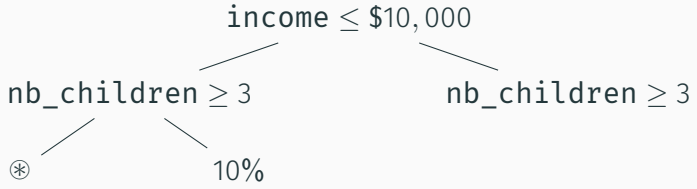

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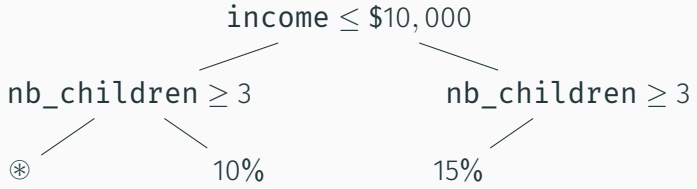

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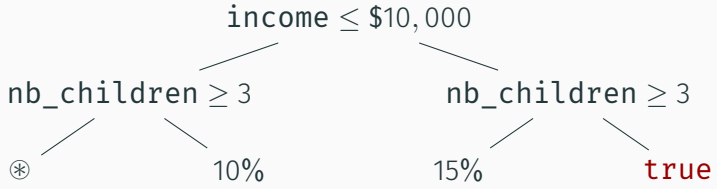

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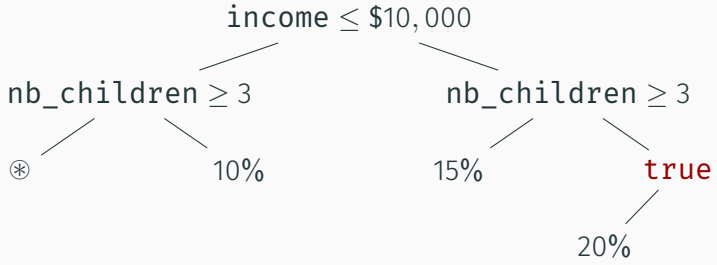

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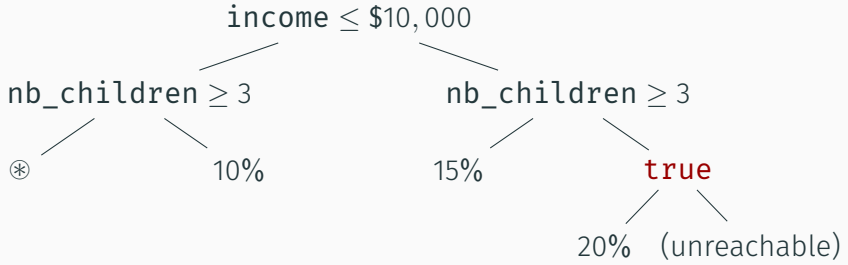
`income` = ???; `nb_children` = ???



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.
$\rightarrow$ it becomes an exception to the exception.

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  | true :- 20%
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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

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

then

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

Performance optimizations using reordering

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

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

then

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

Example:

$$\langle A, B, C, \circledast \mid b_{default} \ :\!- \ e_{default} \rangle \sim \langle \circledast, A, B, C \mid b_{default} \ :\!- \ e_{default} \rangle$$

Performance optimizations using reordering – Example

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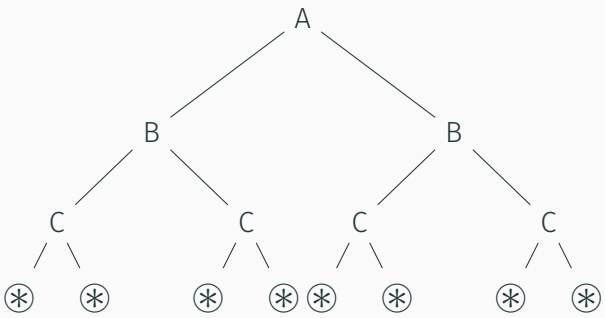

Usability improvement

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# Article 3
If the income is less than $10,000, the percentage
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- Find more usable input values using **soft constraints**

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

Performance optimizations of the solver

- Incremental mode

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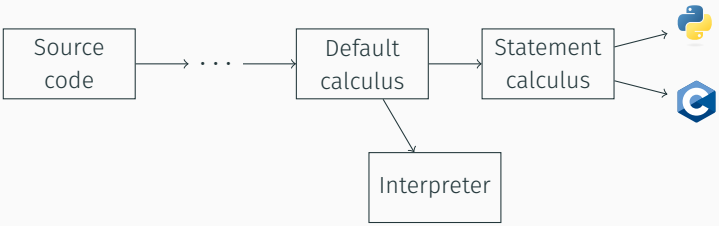
- Redundant constraint elimination

Implementation of CUTECat



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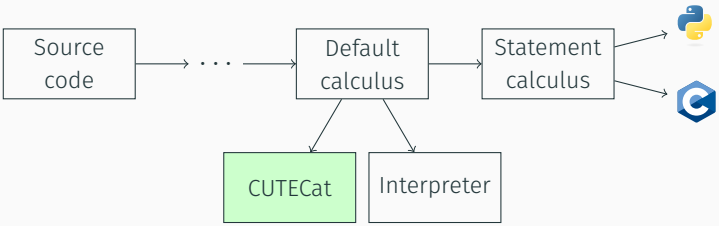

- Integrated into Catala compiler's *default calculus* IR
- 3.4k lines of OCaml code
- **Z3** SMT Solver

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	Incremental	All opt.	Generated tests
US Tax code	0.27	0.02	0.02	10
Minimum wage	1.01	0.08	0.08	17
Family quotient	82.61	5.21	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
- Able to find a conflict

Overhead of the analysis

- 4.5x overhead w.r.t. Catala interpreter
- Optimizations make SymCC[1] or SYMSAN[2] reach the same order of magnitude
- KLEE sometimes reports several orders of magnitude[3]

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[2] Chen et al. [2022]
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- 4.5x overhead w.r.t. Catala interpreter
- Optimizations make SymCC[1] or SYMSAN[2] reach the same order of magnitude
- KLEE sometimes reports several orders of magnitude[3]
- Future work: more optimizations

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Conclusion

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- CUTECat: a concolic testing engine for computational law
- Novel concolic semantics for default logic
- Integrated with Catala toolchain
- Optimizations improve efficiency and usability by lawyers
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Contact, slides: pierregoutagny.fr

References i

Chen, J., Han, W., Yin, M., Zeng, H., Song, C., Lee, B., Yin, H., Shin, I.: SYMSAN: Time and space efficient concolic execution via dynamic data-flow analysis. In: USENIX Security Symposium, pp. 2531–2548, USENIX Association (2022), URL https://www.usenix.org/conference/usenixsecurity22/presentation/chen-ju

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Symbolic vs Concolic execution

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- Possible incompleteness due to mixed integer/rational reasoning
- Lists are hard to encode
- Dates can be ambiguous: what is 29 February 2024 + 1 year?
- We want to generate counter-examples

Fixing the interpretation conflict with labels

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

```
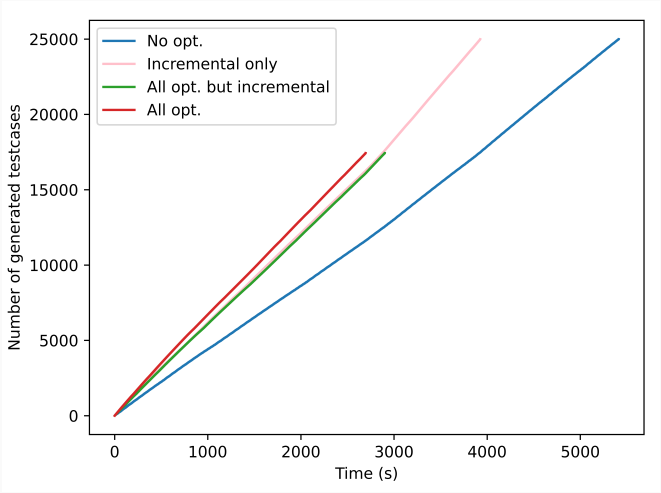
# Article 3
If the income is less than $10,000, the percentage mentioned at article 1 is 10%.
```catala
scope IncomeTaxComputation:
 exception definition tax_rate
  under condition house.income <= $10,000
  consequence equals 10%
```

Article 4
For people in charge of 3 or more children, the percentage mentioned at article 1
is 15%.
```catala
scope IncomeTaxComputation:
 exception definition tax_rate
  under condition house.nb_children >= 3
  consequence equals 15%
```
```

Fixing the interpretation conflict with labels

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

```
# Article 3
If the income is less than $10,000, the percentage mentioned at article 1 is 10%.
```catala
scope IncomeTaxComputation:
 exception children definition tax_rate
  under condition house.income <= $10,000
  consequence equals 10%
```

Article 4
For people in charge of 3 or more children, the percentage mentioned at article 1
is 15%.
```catala
scope IncomeTaxComputation:
 label children
 exception definition tax_rate
  under condition house.nb_children >= 3
  consequence equals 15%
```
```

Ablation study



Generated tests vs time