Validation of models and tests for constrained combinatorial interaction testing

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Intro to validation

- GOAL: finding faults in combinatorial models and test suites
  - Better before test generation and test execution
  - Normally done by hand by domain experts
- We focus on some faults that are detected by the violation of some meta-properties that
  - must be true in any valid model and test suite
  - automatically checked (by an SMT solver)

- **Example**
  - *The constraints do not contradict each others*

Desired (meta)-properties

- For combinatorial models and tests
- **Consistency**
  - requires that there are no elements that conflict with each other.
    - e.g. the constraints should not be contradictory
- **Completeness**
    - e.g. every feasible requirement must be covered by at least one test
- **Minimality**
  - guarantees that the specification does not contain elements defined or declared in the model but never used
  - no over-specification
    - e.g. if a parameter value is never used, it could be removed from the parameter domain
    - e.g. the test suite is minimal

CitLab

- `http://code.google.com/a/eclipselabs.org/p/citlab/`
- Providing testers (and researchers) with some utilities
  - Language (syntax checker) and eclipse-based editor [IWCT12]
  - Test generation via external tools [ICST13]
  - Translators from feature models [IWCT13]

  - IWCT14

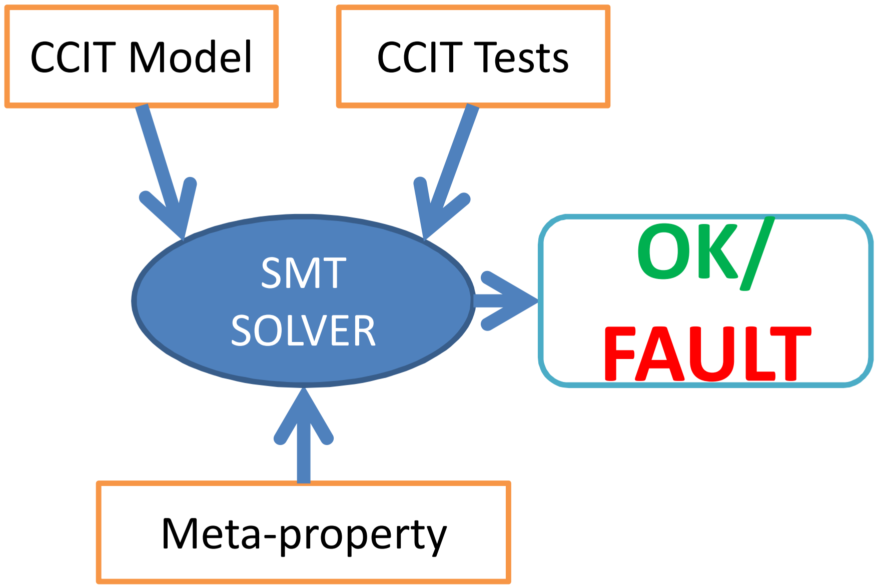
A “semantic” checker for validation

+ a guideline on how to solve these problems

Using SMT solver to prove meta-props

1. CCIT models and tests are translated in the SMT solver as SMT problem
2. Every meta-property is translated into the SMT solver
3. If the property holds (valid) then **OK** else **FAULT**

- **We use the SMT as prover: ϕ valid $\Leftrightarrow$ $\neg\phi$ is sat**



Why SMT ??????
A BDD or SAT is enough, but:

- in the future some new features to the CitLab language (functions, arrays …)
- Some SMT utilities:
  - No need of CNF
  - Incremental resolution

VALIDATION OF CIT MODELS

Inconsistent constraints

A set of constraints $C = \{c_1, \dots, c_n\}$ is consistent iff $\bigwedge_{c \in C} c$ is satisfiable
(i.e. there is a model that satisfies them)
A model is consistent if its constraints are consistent.

- ***Example*** of inconsistent constraints:
  $\{a \wedge \neg b, a \rightarrow b\}$
- In order to discover if a model is consistent, we use the SMT solver by simply checking the satisfiability of the conjunction of the constraints.

How to deal with inconsistent constraints

- In the simplest case a single constraint c_i is inconsistent by itself, i.e., it is a contradiction ($\vDash \neg c_i$).
  - Remove or correct the constraint
  - ***Example***: a=5 **and** a=6

- In most cases there is not a single inconsistent constraint, but the inconsistency derives from the interaction of the constraints
  - ***Example:*** {a ∧ ¬b, a → b, a ∨ b}
  - In this case, the designer may be interested in finding a maximum subset of consistent constraints
    - Greedy algorithm (see paper)

Constraints Vacuity

- Classically a property is vacuously satisfied if that property is satisfied and proved true regardless of whether the model really fulfills what the designer originally had in mind or not
  - Example: the property $a \rightarrow b$ is vacuously satisfied by any model where a is never true.
- Here not the same

> We borrow the term vacuity to indicate a constraint or one of its subformulas which is useless

Constraints Total Vacuity

- Intuitively, a constraint is totally vacuous if it can be removed because it is always true

A constraint c_i is totally vacuous iff

$$\models \left(\bigwedge_{k \in \{1,\dots,n\} - \{i\}} c_k \right) \rightarrow (c_i \equiv true)$$

- With the SMT solver, check the validity of the formula above
- ***Example***: set of constraints C = {¬a, a → b}
  - The constraint a → b is totally vacuous
  - ¬a → (a → b) is valid.
- Any tautology is totally vacuous
- More often constraints contain parts that are useless:
  - Partial vacuity

Reducing a formula

- Given a predicate R, $reduce$ returns the set of all the formulas obtained from R by removing one occurrence of a subformula in R

function $reduce(R)${
 if R is atomic **then return** $\emptyset$
 if $R = a \wedge b$ **then return** $a \wedge reduce(b) \cup reduce(a) \wedge b$
 if $R = a \vee b$ **then return** $a \vee reduce(b) \cup reduce(a) \vee b$
 if $R = \neg a$ **then return** $\neg reduce(a)$
}

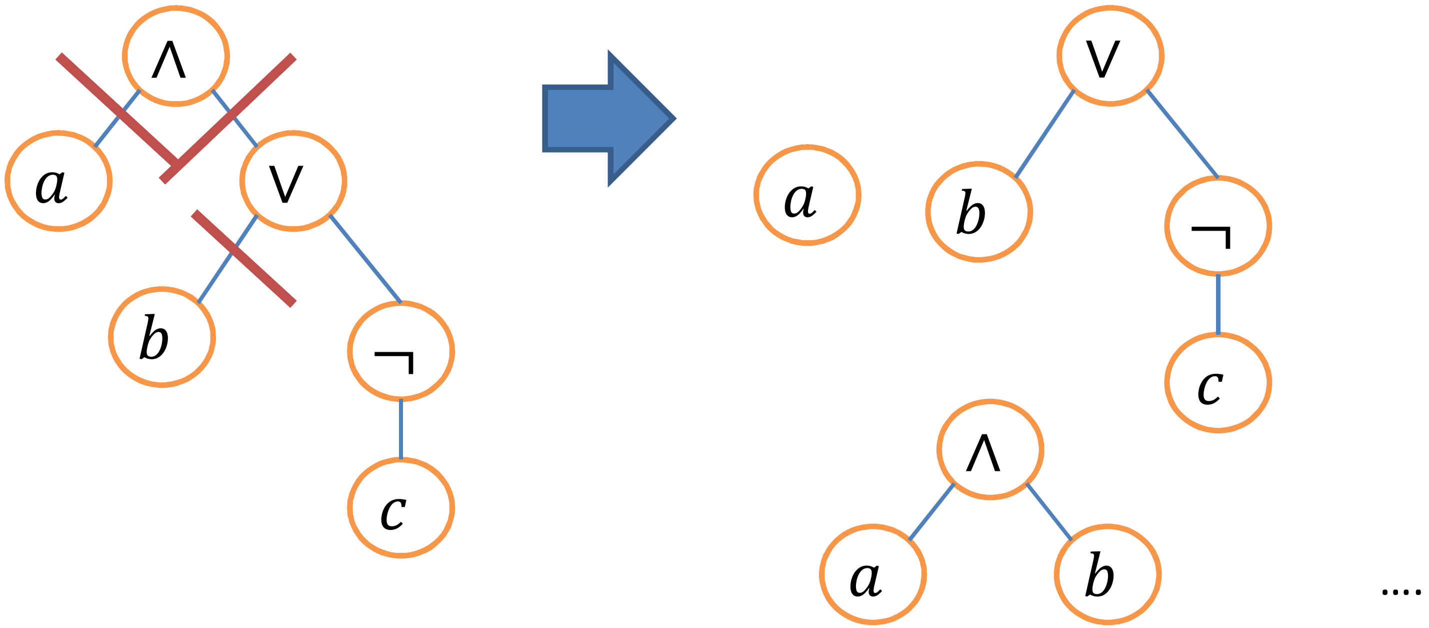
Example:

$reduce(a \wedge b) = \{a, b\}$

$reduce(a \wedge (b \vee c)) = \{a, b \vee c, a \wedge b, a \wedge c\}$

Reducing a formula (tree)

- $reduce$ can be represented as abstract syntax tree “cutting”



Vacuity (general)

A constraint c_i is partially vacuous if there exists ϕ ∈ $reduce(c_i)$ such that $\left(\bigwedge_{k\in \{1,\ldots,n\} - \{i\}} c_k\right) \rightarrow (c_i \equiv \phi)$

- If this is true, then ϕ is equivalent to c_i
  (assuming all the other constraints).
- Using ϕ istead of c_i would give an equivalent simpler model.
- ***Example***: C = {c_1 , c_2 } with c_1= a ∧ b and c_2= (a ∨ b) ∧ d
  REDUCE(c_2) = {a ∧ d, b ∧ d, a ∨ b, d}.

The constraint c_2 is partially vacuous because it is equivalent to d

- c_1 → (c_2 ≡ d) is valid

How to deal with vacuous constraints

- The vacuity of a constraint may actually be caused by an error
  - Correct the error
- If the model and constraints are correct
  1. Simplify the constraints (to speed up the test generation)
     - *Totally* vacuity→ *remove one, check again*
     - *Partial* vacuity →*substitute one with an equivalent subformula and check again*

     Or
  2. The user may be interested to keep extra implied constraints
     - Keep and introduce a new notation **`property`**?

Useless Values and Parameters

- A parameter p can contain in its domain some values which are never taken by p.

The value v of a parameter p is useless if, due to the constraints, p can never assume value v

If the parameter p can assume only a value, then the whole parameter is useless.

- In SMT: v∈ D domain of parameter p is useless, iff $p = v \wedge \left(\bigwedge_{k \in \{1,\ldots,n\} - \{i\}} c_k\right)$ is unsatisfiable.
- ***Example***: `Parameter Enumerative a {a1 a2 a3};`

```
          Constraints:  # a == a.a1 #
```

How to deal with useless elements and parameters

- Uselessness of parameters and values can be caused by errors in the constraints: the test designer may have inadvertently introduced a restriction not present in the real system
  - In this case, the constraints should be revised.
- Otherwise useless parameters and values can be removed from the model
  - To speed up the test generation
  - However, other constraints may require to be modified accordingly.

VALIDATION OF CIT TEST SUITES

Test suite correctness

- A test suite is sound if every test is syntactically correct and valid:
  - an assignment of values to the parameters is a syntactically correct test if it satisfies the type definitions;
  - a test is valid if it does not violate any constraint
- A test suite is complete if every feasible test requirement is covered

Test suite correctness.
A test suite is correct if it is sound and complete.

Checking the completeness of a test suite requires a satisfiability solver, since in the presence of constraints it is not possible to judge if a test requirement is feasible by syntax checking

How to deal with incorrect test suites

- An unsound test suite must be fixed before it can be used.
  - either discard any invalid test or
    - It may reduce the coverage
  - Or modify it in order to make it valid
    - It may be difficult
- An incomplete test suite can be completed
  - For instance by using a test generator tool that accepts an existing possibly incomplete test suite (often called seeds)

- Incorrect test suites signal a fault of the test generation algorithm: useful for researchers when experimenting and implementing ne techniques

Test suite minimality

- A test generally cover several other tuples covered by other tests
  - Redundancies
- Some tests that overlap may be eliminated without reducing the total coverage of the test suite.
- test suite reduction or minimization

A test suite TS is minimal if there exists no subset $TS' \subset TS$ such that TS' satisfies all the testing requirements as the original set TS does, i.e., that all the tuples covered by TS are also covered by TS

- How to recognize a non-minimal test suite?

Test suite minimality check

- A test case t_i is essential if it covers at least one tuple in TP (the set of all the tuples for a given n-wise coverage) not covered by other test cases of the test suite TS.
  - Formally, $\exists \mathrm{tp} \in \mathrm{TP}: t_i \vDash \mathrm{tp} \land (\neg\exists t_i \in \mathrm{TS}: (i \neq j \land t_j \vDash \mathrm{tp}))$

A test suite TS is non-minimal iff TS contains at least a not essential test.

How to deal with non minimal test suites

- Not essential tests can be removed
  - Not at once: removing a not essential test may make others essential…
- Test suite reduction (also known as test suite minimization) is often applied in regression testing
  - The problem of finding the minimal test suite that satisfies a set of test goals can be reduced, in polynomial time, to the minimum set covering problem which is NP-hard.
- A simple greedy heuristic for the minimum set covering problem defined can be adapted to the test suite minimization.

EXPERIMENTS

Experiment setup

- A set of 64 models with constraints taken from the literature
  - CASA (M. B. Cohen, M. B. Dwyer, and J. Shi)
  - FoCuS (I. Segall, R. Tzoref-Brill, and E. Farchi)
  - ACTS (Y. Lei, R. Kacker, D. R. Kuhn, V. Okun, and J. Lawrence)
  - IPO-S (A. Calvagna and A. Gargantini)
- used in most papers

- SMT solver yices http://yices.csl.sri.com/

Good news

- No benchmark contains inconsistent constraints
- No tool (ACTS, CASA, ATGT) produced incorrect test suites

- Somehow expected because the models are used in the literature and the tools are validated by other experiments
  - Future work: use during model design or to setup ne algorithms

1. Vacuity detection

- 37 models presented at least one vacuity
  - More than 50% of the benchmarks
  - *bench_n*: randomly synthetized from real case studies [CASA]
  - But others as well
    - See table

	Vacuous subformalas	Vac. constraints
CommProt	814	76%
Concurr	7	14%
gcc	6	5%
HealthC2	14	8%
ProcComm2	43	83.2%
Services	81	7%
SmartHome	33	77%
Storage1	205	43%
Telecom	5	5%

2. Useless values and parameters

- 23 models have at least one useless parameter value or one useless parameter
- 21 *bench_n*
  - Ok, but they should be fixed
- ProcComm2
  - ``real-life test space instance generated by or for our customers'
- SmartHome
  - From a Feature Model: useless parameters are present because the model has been automatically obtained from a feature model without applying any optimization.

Are we sure they are good benchmarks?

3. Non minimal test suites

- ACTS in two cases (3% of all the cases) produced non minimal test suites
  - However, still very easy to find and fix

Conclusions

- Validation of combinatorial models and tests by proving some semantic meta-properties:
  - Consistency and not vacuity (total or partial) of constraints,
  - Utility of parameters and elements
  - Correctness and minimality of test suites
- Requires a solver (SMT in our case)
- How to deal with them? Still open problem.
- Useful for users and researchers

Thank you