E0:272 Formal Methods in Software Engineering

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Tue-Thu 2:00 - 3:30

http://csa.iisc.ac.in/~deepakd/fmse-2026

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Motivation

- Software is increasingly used in a wide range of domains: business, personal, scientific, embedded control.
- Therefore, software development ought to
  - be efficient and predictable
  - result in high quality (i.e., correct and reliable) software
- The way to achieve this is to use automated analysis tools
- Methodology of the course: Hands-on study of a series of advanced tools
- Knowledge of such tools gives
  - Exposure to practical uses of various analysis techniques
  - Generates research ideas for developing better tools
  - Prepares one for career in software-development industry

Software development is hard

Average software-development project [Barry Boehm, ICSE '06 keynote] incurs:

- 90% cost overrun
- 121% time overrun
- delivers only 61% of initially promised functionality

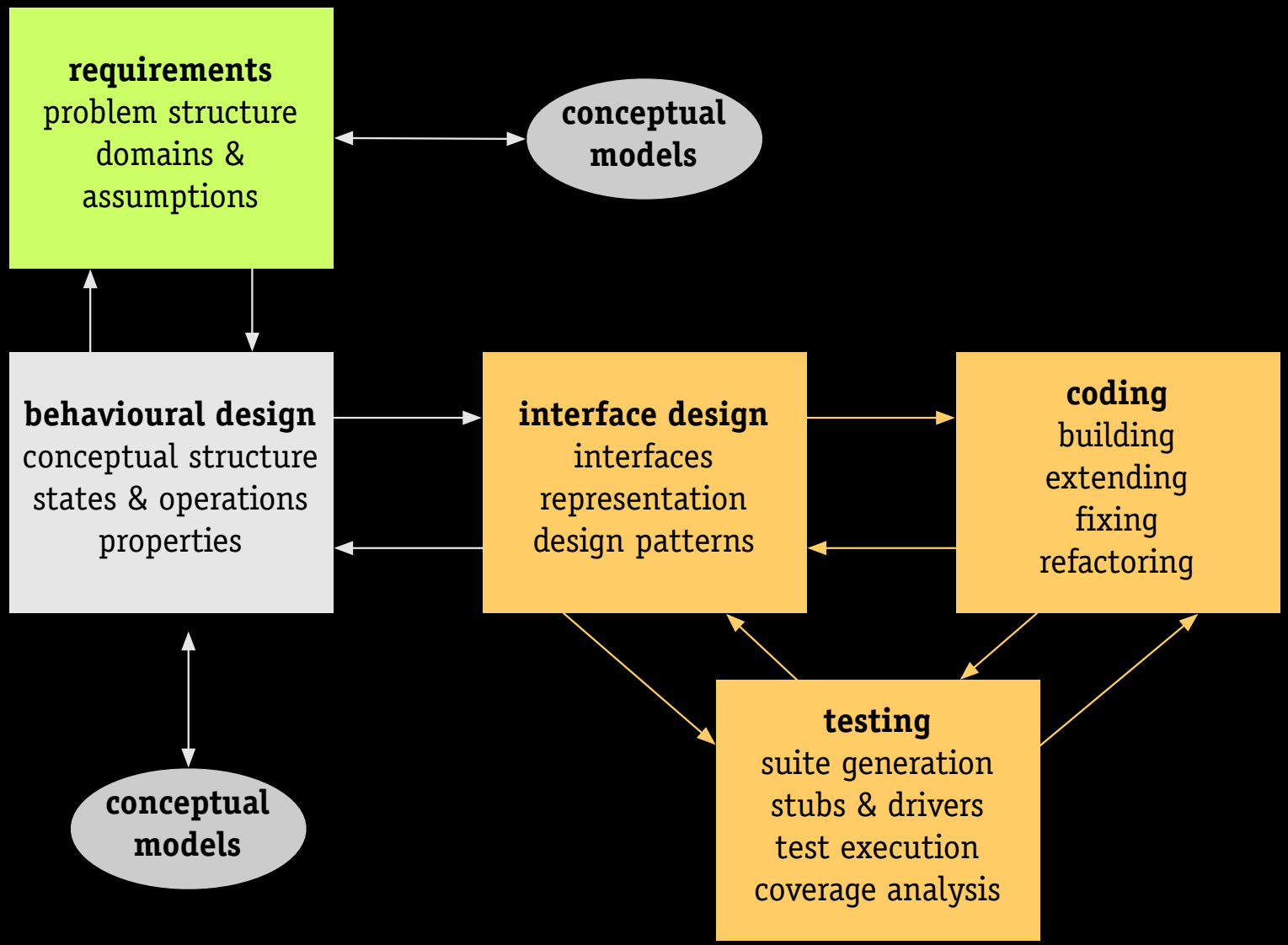
Software defects

- Most large software is buggy
- They cause user dissatisfaction, and sometimes catastrophe (e.g., Ariane 5 rocket explosion)
- Finding and fixing bugs consumes 50% of the total effort in software development!

Causes of software defects

- User's requirements not specified properly.
- Software does not meet user's requirements.
- Implementation errors
  - Low-level errors, such as null-pointer dereference, array out of bounds
  - Different components of the software (or software and libraries) evolve separately, and become inconsistent.

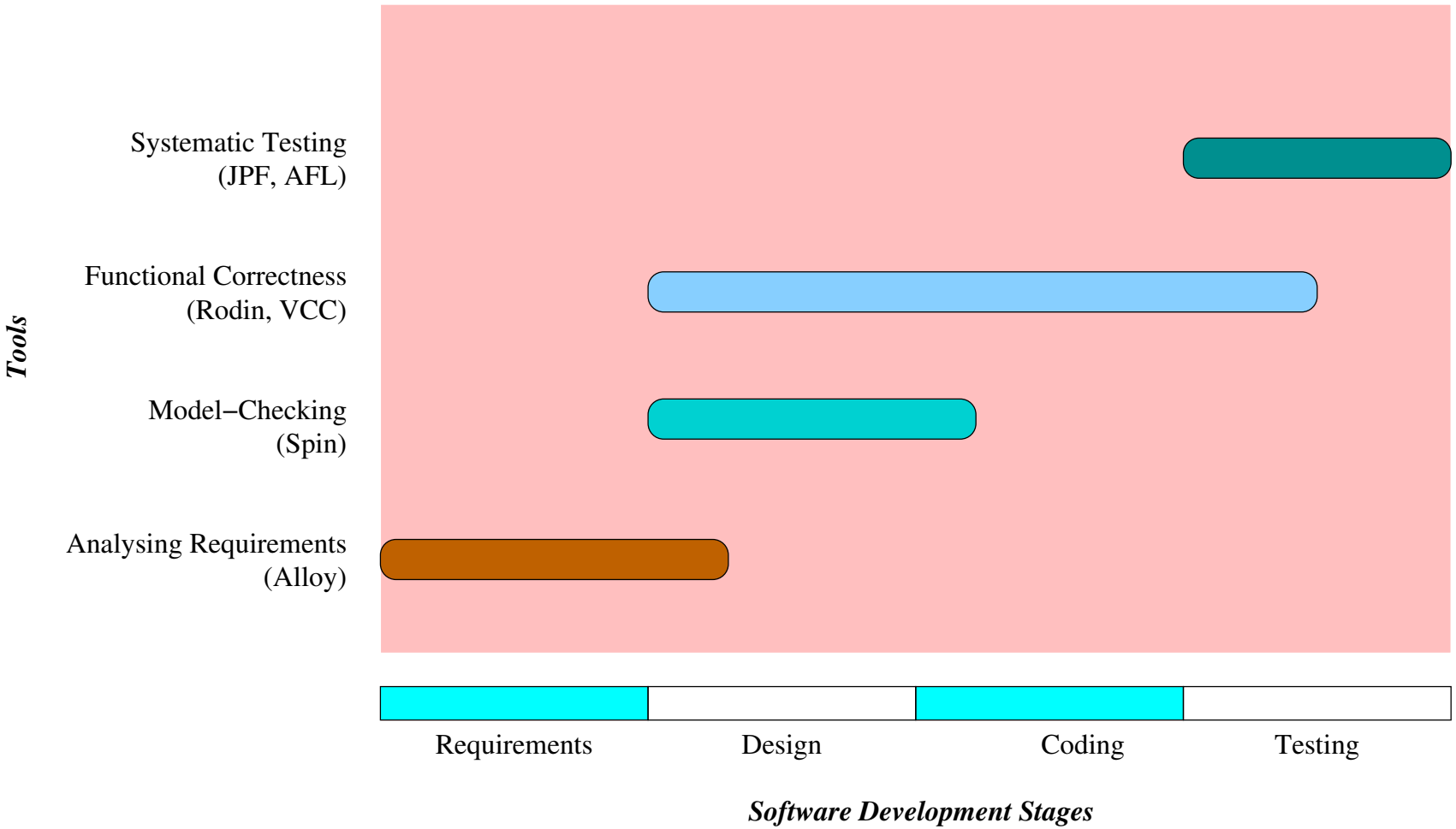
two kinds of design



The solution to the problem: tools

- Tools are available for all stages of software development
- Benefits of tools
  - Tackle complexity by providing abstract views of software
  - Identify errors by exhaustive analysis
  - Provide reliable way to make changes
  - Make software development more like engineering, and less of an art
- Our focus is mostly on
  - Formal tools, that provide definitive guarantees, and
  - Involve non-trivial capability for analysis or transformation.
  - We will cover only a small selection of the tools available!

Methods and tools covered in this course



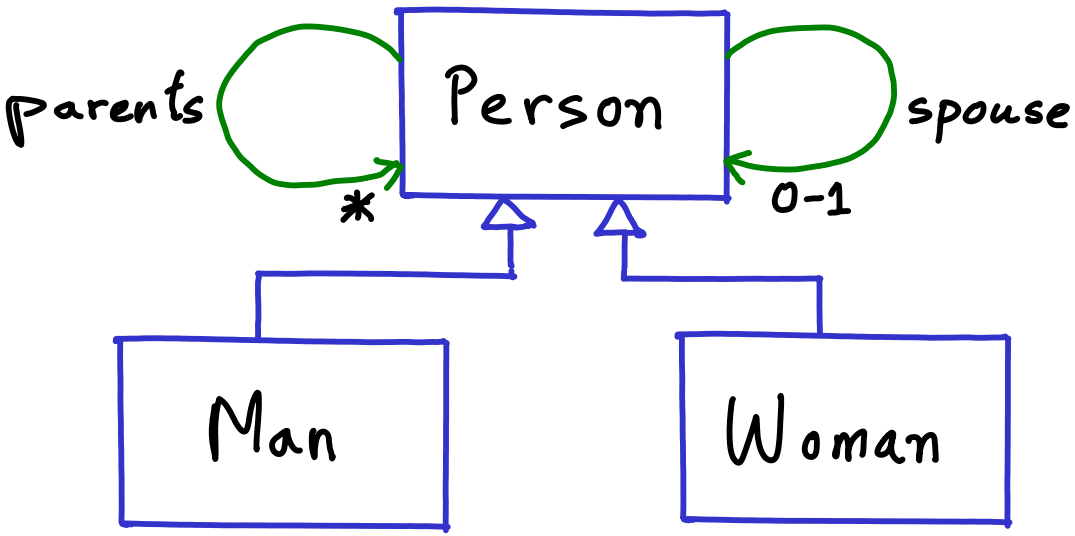
Tools for conceptual modeling and design

- Alloy (Conceptual modeling)
  - Formalize key entities in the domain, their relationships between them, and the operations that can be performed on them.
  - Helps identify inconsistencies and incompleteness in requirements.
- Spin (Modeling/design)
  - Specify states in the system, and the transitions between them.
  - Identify the properties of the sequences of states that can arise.
- Rodin (Modeling/design)
  - Step-wise refinement of a conceptual model, with guarantee of preservation of all properties.
  - Ultimately: refine to code level.

Overview of Alloy

- Formal modeling of entities and relationships, using sets and relations
- Modeling of invariants/constraints on the entities
- Analyzing consistency of the model, and identifying errors

Example – keeping track of family relationships



Examples of desired constraints

- Every person has two parents, one man and one woman
- Parents of any child are married
- Cannot marry a sibling or a parent
- Every person is married to at most one person
- a married to $b \Rightarrow b$ is married to a
- A man can only marry a woman, and vice versa

Key elements of Alloy model

- `abstract sig Person`
  - `Person` is a *abstract* entity (i.e., with no concrete instances).
- `sig Man, Woman extends Person {}`
  - `Man, Woman` are subtypes of `Person`.
  - No other subtypes. Therefore, every instance of `Person` is an instance of either `Man` or `Woman`.
- `spouse` is a relation mapping each `Person` to zero or one `Person`
- `parents` is a relation mapping each `Person` to zero or more `Persons`
- Constraints

```
fact {
    all p: Person | one mother: Woman | one father: Man |
      p.parents = mother + father // every person has a mother and father
    spouse = ~spouse  // spouse is symmetric
    Man.spouse in Woman && Woman.spouse in Man
     // a man's spouse is a woman and vice versa
}
```

Results of using Alloy on above example

- Our rules are too relaxed. They allow instances wherein a person is their own grandparent.
- We could add an extra rule (i.e., `fact`) that no person be their own grandparent. However, with this, there are no non-trivial instances!

Model checking using Spin

- Given an abstract model like a state machine, and a specification of desired behaviour of all traces (typically in temporal logic), the tool tries to verify that the model satisifes the property.
- If not, it produces a counterexample: a behaviour of the model that violates the property.
- Similar to Alloy, but checks traces of a state machine rather than entities and relationships.

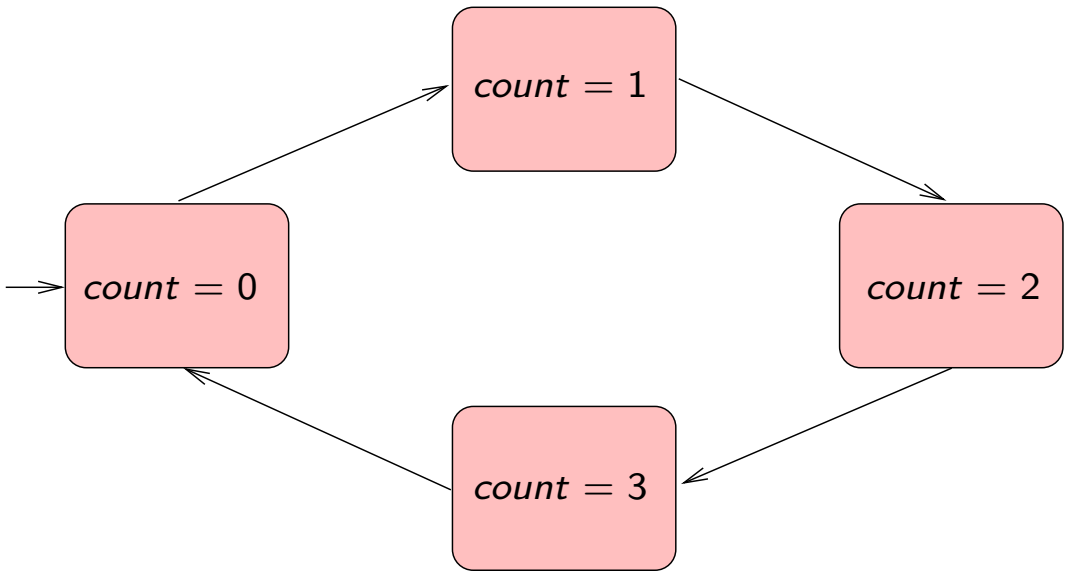
Model-Checking and Spin

Spin is a model-checking tool, in which we can

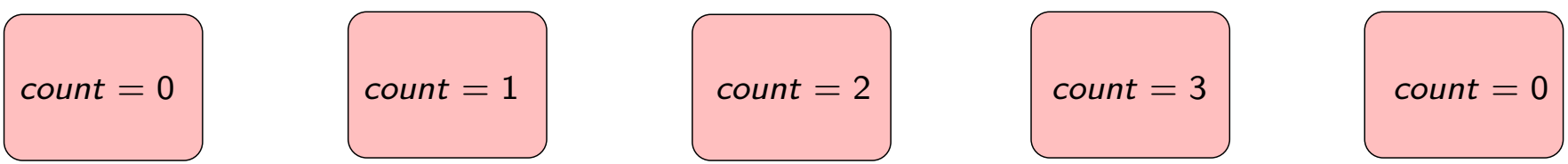
- Describe transition system models.
  - Suited for concurrent protocols, supports different synchronization constructs.
- Simulate them, explore paths in them.
- Describe desirable properties of the system in temporal logic.
- Check that the system satisfies these properties.
  - Proves that property is satisfied
  - Produces counter-examples (execution that violates property).

Example transition system: a mod-4 counter

Diagrammatic representation



Example run:



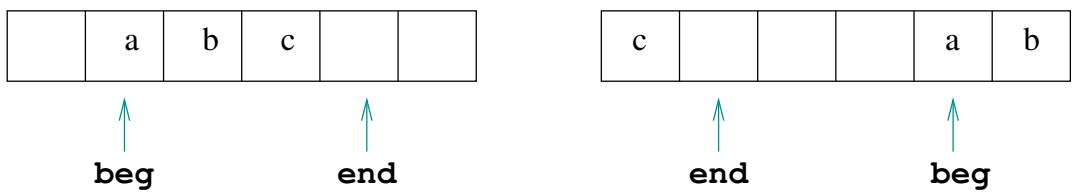
Example properties for counter model

```
byte count = 0;

proctype counter() {
  do
  :: true -> count = (count + 1) % 4;
              assert (count <= 3);
  od
}

init {
  run counter();
}

ltl prop1 { [](count <= 3) };
ltl inc { []((count == 1) -> X(count == 2)) }
ltl prop3 { ((count == 0) || (count == 1)) U (count == 2));
ltl prop4 { [](count == 0) };
```

Rodin and Refinement: C implementation of a queue

```
 1: int A[MAXLEN];
 2: unsigned beg,
     end, len;
 3:
 4: void init() {
 5:   beg = 0;
 6:   end = 0;
 7:   len = 0;
 8: }
 9:
10: int deq() {...}
```

```
11: void enq(int t) {
12:   if (len == MAXLEN)
13:     assert(0);
        // exception
14:   A[end] = t;
15:   if (end < MAXLEN-1)
16:     end++;
17:   else
18:     end = 0;
19:   len++;
20: }
```



How does one prove functional correctness?

Tools for implementation and testing

- Verification tools [VCC]
  - Guarantee that a program returns correct output in all runs.
  - Programmer needs to specify formally correctness of program output
  - Programmer also needs to specify intermediate properties that need to hold at various program locations in order for final output to be correct. Otherwise, tool may fail to work or may report false warnings.
- Automated testing tools [JPF, AFL]
  - Based on actually executing the program on test-cases.
  - Both tools automatically generate test inputs one after the other, to try to reach more and more parts of the program.
  - Developer would need to specify a way to check correctness of output from each run. However, developer need not annotate intermediate program locations with intermediate properties.
  - All bugs found are true bugs.
  - However, can miss bugs.

Prerequisites

- Discrete structures such as sets, relations, partially ordered sets, functions
- Mathematical logic (propositional, first-order)
- General mathematical maturity: comfort with notation, understanding and writing proofs
- Familiarity with languages C/C++ and Java
- (Moderate) programming experience

Lecture format

- Theory and algorithms behind the tools
- Demo of tools

Assignments and exams (tentative)

- Assignments (50%). Each assignment will involve
  - applying one or more tools practically, and
  - a few written problems
- Exams: mid-sem (25%), final (25%).
  - Will have practical (lab) component.
  - Internet access not allowed during exam. You can bring class materials and documentation with you.

Misconduct policy

- Academic misconduct (e.g., copying) will not be tolerated
- Discussion in exams ⇒ automatic fail grade for both students
- Assignments
  - Work individually.
  - If necessary, you can seek clarifications on basic concepts from other students.
  - However, you must develop the solutions to the given problems on your own (without discussions), and write the programs or answers on your own.
  - No looking at others solutions, no showing your solution to others!
  - If you refer to materials other than class lecture notes and text books, and especially if you use AI tools, write in your answer book the exact way in which you used these.
- Penalties
  - For *each* instance of a violation of above policy ⇒
    Zero for the entire assignment, *plus* one grade-point reduction in final grade (for the one who copied).
    - Grade-point reductions over multiple violations will accumulate.

Late submission policy for assignments

- For each late day 20% penalty on the assignment marks. (Weekends and weekdays treated the same.)