ECE 587 – Hardware/Software Co-Design
Lecture 03 State-Based Models I

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Reading Assignment

- This lecture: 3.1, 3.1.2
- Next lecture: 3.1.2

Outline

Models of Computation

- Any non-trivial functionality must involve some kind of computation.
- It is beneficial to specify the functionality just at the abstraction level of the computation.
  - It's intuitive.
  - Computations are behavioral. No implementation detail is necessary.
  - Computations are based on mathematics. There may exist tools to automate the remaining design process.
- Models of Computation (MoCs)
  - Serve as basis to reason about computation/constraints
  - Utilize formal language, e.g. certain kind of mathematics
  - May have different supported features, complexity, and expressive power.

Common MoCs

- MoCs define computations by specifying when to perform operations.
  - The time here is not absolute time but relative ordering.
  - So ultimately it depends on how synchronizations are employed.
- Fully synchronized model: Finite State Machine
- Fully ordered without synchronization: Sequential Programs
- No synchronization at all: Dataflow
- We will first focus on FSM and move to other models in the next few weeks.

Outline

Finite-State Machine (FSM)

$$< S, I, O, f, h >$$

- Set of states S
- Set of input symbols I
- Set of output symbols O
- Next-state function $f : S \times I \rightarrow S$
- Output function $h : S \times I \rightarrow O$
- Some systems may specify initial states and/or final states

What is *not* specified?

- Encoding of states and input/output symbols in HW/SW
  - This condition will sometimes be relaxed so one can handle extremely large systems.
- Implementation of f and h in HW/SW

Representations of FSM

- Graph representation
  - States as vertices
  - State transitions as edges (annotated with inputs/outputs)
  - Intuitive, but if there are too many possible states, it becomes unmanageable.
- Functional representation
  - If one can efficiently specify f and h, then the FSM can be simulated from any initial state and a trace of inputs, fulfilling most computational tasks.
  - Can handle extremely large systems

Encodings

- Since a FSM has a finite number of possible states, one can represent, or *encode*, a state using a fixed number of bits.
  - E.g. if there are 16 possible states, a 4-bit encoding can be applied.
- Similarly you can encode inputs and outputs.
- Under such encodings, the functions f and h become boolean functions.

FSM vs. Register Transfer Level (RTL)

- That's exactly how RTL is defined.
  - Just change the state bits to registers
- The key here is encoding.
  - Encoding enables us to specify extremely large FSMs.
  - Different encodings may lead to specifications with different complexity, though for system design we prefer to use the most intuitive one.
- We will still distinguish functional representations of FSM from RTL as they have different purposes.
  - Though mathematically there is no difference.

Implement FSMs

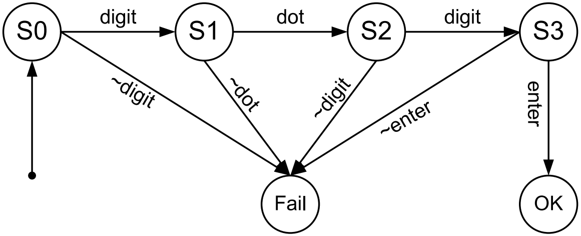
- Hardware: as Synchronous Circuits
  - Utilize the connection between functional representation and RTL
  - Exactly one state transition happens per clock cycle.
  - High speed/low power/energy consumption
  - Usually known as cycle-accurate behavior
- Software: follow either graph or functional representations
  - Tedious, better to have tools to generate code
  - Not efficient in both time and power
  - But is a very powerful architecture to build complex software that needs to react to external events, e.g. networking and graphical user interface.

Outline

Input Validation

- Consider an application that requires to validate user inputed numbers
    - Assume the input is a character string
    - End of string must be `enter`.
- A valid integer
    - If the first character is not a digit, then it must be either $+$ or $-$.
    - Except the first character and the ending `enter`, all characters are digits.
    - The most significant digit must not be 0.
    - The integer may contain arbitrary number of digits.
- Additional tasks
    - Deal with floating-point numbers
    - Extract the number during validation
    - Implement the designs in a programming language.
- How to approach this or similar problems?

A Simple FSM



- How does it work?
  - Starting from S0
  - Process exactly one character per transition.
- This simple example accepts numbers like 1.2, 4.5, but not 11 or 1.21.

A More Complex FSM

- Build a FSM to recognize integers.
- Extend it to handle floating-point numbers.

Extract Numbers

- Focus on integers but make it easy to extend our solution to floating-point numbers etc.

Software Implementation

```
enum {S0, S1, ..., OK, FAIL};
int state = S0, sign = 1, num = 0;
while ((state != OK) && (state != FAIL)) {
  int next_state = state; // assume state remain the same by default
  int ch = read_one_input();
  if (state == S0) {
    if (ch == '-') {
      next_state = S1; sign = -1;
    } else if (isdigit(ch)) {
      next_state = S1; num = ch-'0';
    } ...
  } else if (state == S1) {
  } ...
  state = next_state;
}
num *= sign;
```

- Make use of a single loop to drive the state transitions.
- Use two levels of branches to handle combinations of current state and input.
- It can handle *any* FSM no matter how complicated it is.

Discussions

- From the FSM model, it will be much easier for the designers to utilize tools at hand to implement the validation as either hardware or software.
- Such problems are special cases of *Regular Expressions*.
    - It is used almost everywhere when text is processed.
    - Many places require to run it very efficiently, e.g. to filter certain information from the network at realtime.
- Regular expressions can be modeled by a special kind of FSMs called nondeterministic FSM.
    - There is a mapping from graph representation of nondeterministic FSM to RTL, which enable one to implement it quite efficiently in hardware.
    - The challenge in hardware implementation is reconfigurability without much overhead.
    - Software implementations are based on the same idea but are much more awkward.