Foundations for the Run-time Monitoring of Reactive Systems

-Fundamentals of the MaC language

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Motivation and Focus

- Motivation
  - As more computer systems are deployed in daily life, more needs on the correctness of the computer systems
  - Monitoring, as a complementary method to formal verification and testing, can increase assurance of systems
- Two Focuses
  - Theoretical description on the power of monitoring
    - Accurate description of monitorable languages
      - Subset of the class of safety languages equivalent to Π_1^0
  - Practical framework of monitoring
    - Monitoring and Checking (MaC) architecture
      - Proof of expressiveness for general monitoring purpose

Outlines

- The Class of Monitorable Languages *M*
- *M* in the Arithmetic Hierarchy
- ω-automata with storage
- The Monitoring and Checking (MaC) framework
- Conclusion

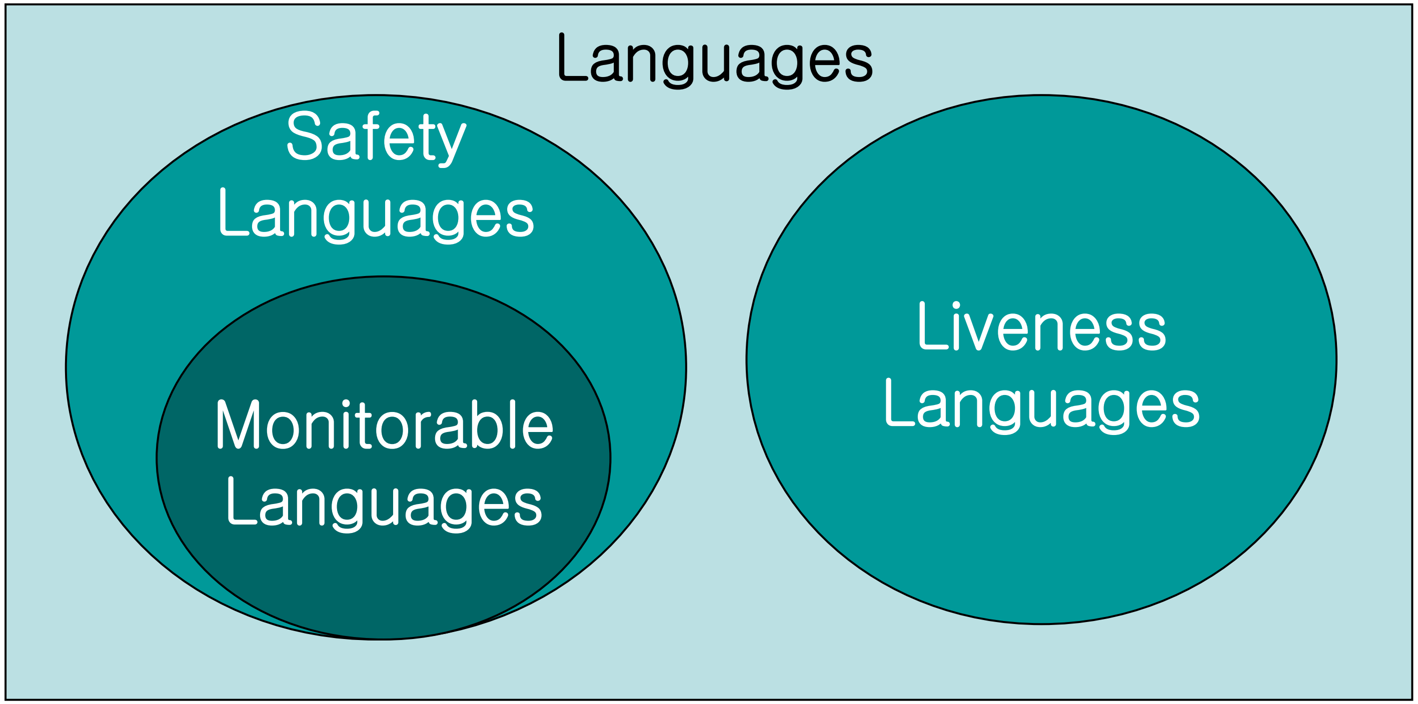
Safety Languages

- A language is a set of program executions
  - An execution of a program is an infinite sequence of program states S
- Safety languages are languages that require that nothing bad happens during an execution
  - Monitor should be able to reject faulty execution after looking at a finite prefix
  - A language L is a safety language if $\sigma \in L$

    iff $\forall i \, \exists \beta \; s.t. \; \sigma(0,i) \cdot \beta \in L$

Relationship among Languages

- Safety languages ≠ monitorable languages



Monitorable Languages

- Example
  - $\sum = \{0,1,a,b\}$
  - $H_* = \{ x \cdot a \cdot y \mid x, y \in \{0,1\}^*$, the Turing Machine encoded by x halts on input $y\}$.
    - Membership of H_* (the halting problem) is undecidable
  - We can define a safety language

$$H_\omega = (H_* \bullet b^\omega) \cup (\{0,1\}^* \bullet a \bullet \{0,1\}^\omega) \cup \{0,1\}^\omega$$

Monitorable Languages (cont.)

- A language $L \subseteq S^{\omega}$ is monitorable iff
  - L is a safety language
  - $S^{*} \backslash \mathrm{pref}(L)$ is recursively enumerable
- Let us call the class of monitorable languages $\boldsymbol{M}$

Definition of Π^0_1

- Arithmetic Hierarchy
  - Hierarchy of languages over the class of recursive relation C
  - L *is in* Π^0_n *if and only if* for some $R \in C$

    $L = \{\alpha \mid \forall v_1 \exists v_2 \ldots Q_n i.\ R(v_1, v_2, \ldots, \alpha(0,i))\}$
- An infinite language L is in Π^0_1 if and only if for some recursive relation R

  $L = \{\alpha \mid \forall i.\ R(\alpha(0,i))\}$

- $\Pi^0_1 \Rightarrow M$
  - Suppose $L \in \Pi^0_1$
  - *1.* L is a safety language from the def of Π^0_1
  - *2.* $u \in \Sigma^*\backslash\mathrm{pref}(L)$ iff $\neg R u$

    $\Rightarrow \Sigma^*\backslash\mathrm{pref}(L)$ is recursively enuerable.

  (one way proof done)
- $M \Rightarrow \Pi^0_1$

ω-automata with storage

- Storage type
- ω-automata with a storage
- Equivalence results

Storage type

- A storage type is a 5-tuple $X = (C, C_0, P, F, [])$
  - C: a set of storage configurations
  - C_0: a set of initial storage configuration
  - P: a set of predicate symbols
  - F: a set of function symbols
  - []: a function that defines the semantics of P and F
    - [p]: C -> {true,false}
    - [f]: C ->C
- Ex. Accumulator storage type
  - $AC = \{N, \{0\},\{zero\},\{+_k,-_k\},[]\}$

ω-automata with a storage

- An X-automata is a 5-tuple $(Q,\Sigma,\delta,q_0,c_0)$
  - $\delta \subseteq Q \times (\Sigma \cup \{\varepsilon\}) \times BE(P) \times Q \times F^*$
- The class of ω-languages accepted by X-automata will be denoted by XL

ω-automata with a storage N_m

- N-fold product of a storage type X: X^n
- The storage type of m integer

  $N_m = (C, C_0, P, F, [])$

  - $C = N^m$, $C_0 = \{<0,\ldots 0>\}$, $P = \{zero_i \mid 0 <= i < m\}$,
  - $F = \{ADR_{i,j}, SBR_{i,j}, ADC_{i,k}, SBC_{i,k}, MLC_{i,k}, QC_{i,k}, RMC_{i,k}\}$
- $N_* L = \cup_m N_m L$

ω-automata with a storage

- Characteristics of an *X*-automata
  - *d*-:deterministic
  - *r*-:real-time (no ε transition)
  - *f*-:finite delay (no infinite runs on a finite word)
- The following classes of ω-languages are equivalent

  1) $M = \Pi^0_1$

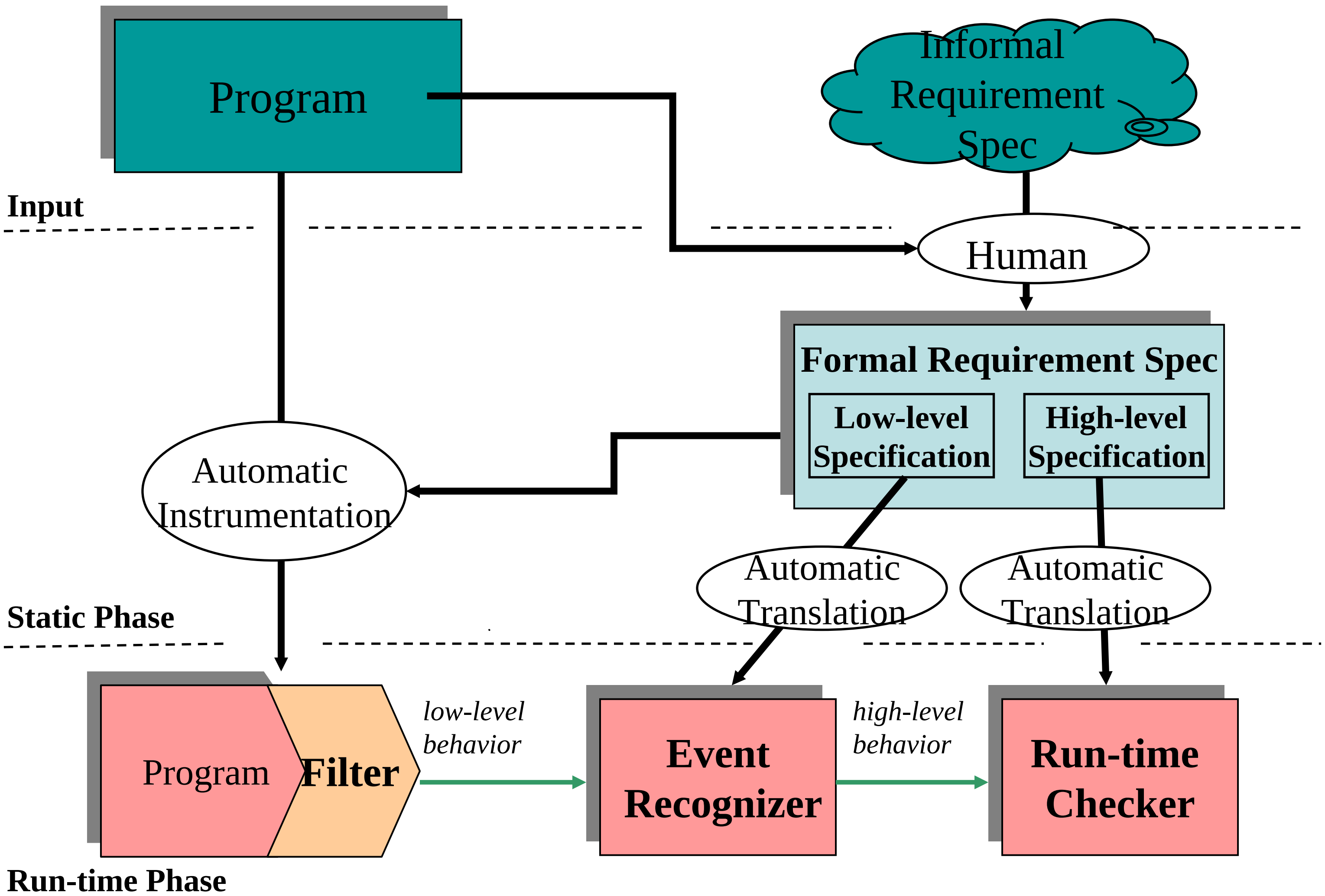
  2) $df\text{-}N_*L$

  3) $dr\text{-}N_*L$

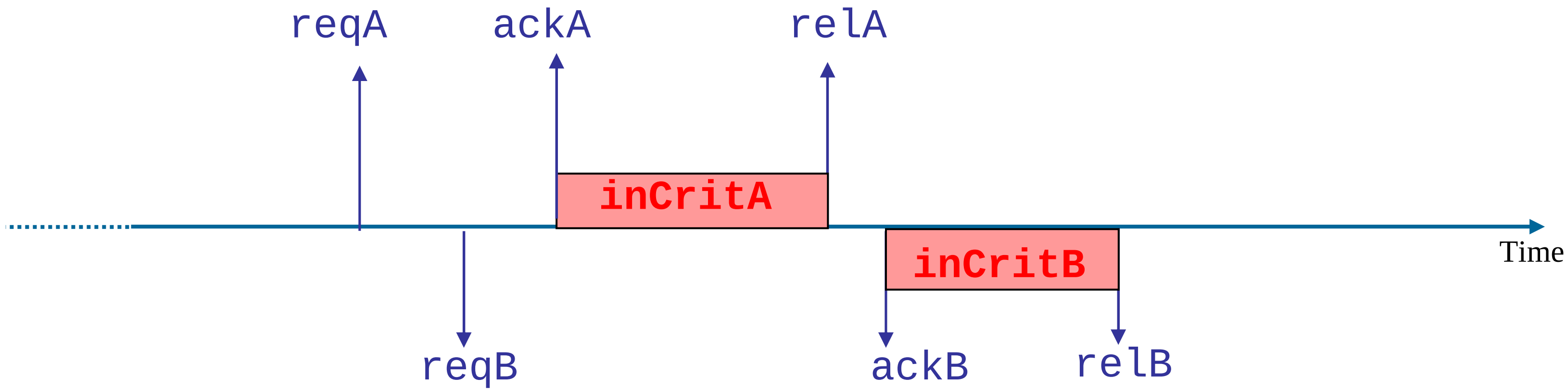
Proof Sketch

- $M = \Pi^0_1 \Rightarrow df\text{-}N_*L$
  - For a language $L \in \Pi^0_1$, $\alpha \in L$ iff $\forall i.\ R(\alpha(0,i))$ where R is a ***recursive*** language. Therefore, there exists a deterministic finite delay N_m-automaton which accepts exactly the same words as *R*.
- $df\text{-}N_*L \Rightarrow dr\text{-}N_*L$
  - The real-time automaton reads an input symbol every time and puts it into the ***buffer***, while the actual computation is then performed on the buffered input.
- $dr\text{-}N_*L \Rightarrow M = \Pi^0_1$

Overview of the MaC Architecture



Design of the MaC Language



- Must be able to reason about both time instants and information that holds for a duration of time in a program execution.
  - Events and conditions are a natural division, which is also found in other formalisms such as SCR, durational calculus, interval logic, etc
- Need temporal operators combining events and conditions in order to reason about traces.

Logical Foundation

$$C \ ::= \ c \ |\text{defined}(C) \ | \ [E_1, E_2) \ | \ \neg C \ | \ C_1 \vee C_2 \ | \ C_1 \wedge C_2$$

$$E \ ::= \ e \ | \ \text{start}(C) \ | \ \text{end}(C) \ | \ E_1 \vee E_2 \ | \ E_1 \wedge E_2 \ | \ E \ \text{when} \ C$$

- Conditions interpreted over 3 values: true, false and undefined.
- [., .) pairs a couple of events to define an interval.
- `start` and `end` define the events corresponding to the instant when conditions change their value.

Meta Event Definition Language (MEDL)

- Expresses requirements using the events and conditions
- Expresses the subset of safety languages.
- Describes the *safety requirements* of the system, in terms of conditions that must always be true, and alarms (events) that must never be raised.
  - property safeRRC **`= IC -> GD;`**
  - alarm violation = start (!safeRRC);
- *Auxiliary variables* may be used to store history.
  - endIC-> { num_train_pass' = num_train_pass + 1; }

```
ReqSpec <spec_name>

  /* Import section */
  import event <e>;
  import condition <c>;

  /*Auxiliary variable */
  var int <aux_v>;

  /*Event and condition */
  event <e> = ...;
  condition <c>= ...;

  /*Property and violation */
  property <c>  = ...;
  alarm <e> = ...;

  /*Auxiliary variable update*/
  <e> -> {  <aux_v'> := ... ; }
End
```

Expressive Power of MEDL

- MEDL is expressive enough for *M*
- Proof sketch: for every *dr*-N_*-automaton *A*, there exists a MEDL script
  - The input alphabet of *A* will be all the imported events
  - Auxiliary variable for each of the *m* storing locations
  - Auxiliary variable `state`
  - A transition (*q1*,*a*,*b*,*q2*,*f*) is transformed into a guard (a && E_b) `when` (`state`==q1) `->` {`state`':=q2;f';}

Conclusion

- We show that the class of monitorable language is ***strict subset*** of safety languages
- MEDL, the specification language of the MaC framework is ***expressive enough*** for the class of monitorable languages *M*
- Working on extension of MEDL for easy property description