Advanced model checking for verification and safety assessment

Part 2
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Sixth Summer School on Formal Techniques (SSFT’16)

Lecture prepared in collaboration with
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Some slides borrowed from Cristian Mattarei, Marco Bozzano, Anthony Pires
Lecture 2

- Safety Assessment
  - Fault Extension
  - Fault Tree Computation
- Requirements Analysis
- Contract Based Design
- Contract-Based Safety Assessment
- Case-Studies
  - WBS
  - NASA
- Wrap-up
Safety Assessment
Safety Assessment

The **safety assessment process** provides a **methodology** to evaluate the design of systems, and to determine that the **associated hazards** have been properly addressed...

...and it should be planned to provide the **necessary assurance** that all relevant failure conditions have been **identified and considered**.

*Aerospace Recommended Practice 4761*

*SAE International*
Model-Based Safety Assessment (MBSA)

- Used for the evaluation of safety critical systems e.g., redundancy / fault tolerance
- The nominal system description is extended by allowing faulty behaviors (fault injection)
- Find all possible fault configurations that may cause the reachability of an unwanted condition (a.k.a. Top Level Event - TLE)
  - Assume $M \models \phi$
  - $\text{TLE} := \neg \phi$
    - Bad states in case of invariant property
    - Generalized also to LTL
Model Extension

- From **nominal** $M := \langle V, I, T \rangle$ to **extended** $M^X := \langle V^X, I^X, T^X \rangle$ model, where $V \cup F \subseteq V^X$

- Extended model with disabled fault variables (i.e. set to FALSE) should have the same behavior as the nominal one

- **Symbolic Fault Injection**, additional behavior in parallel to the nominal one, selected via a mode selector:
Model-Based Fault Injection

- Nominal behavior
- Faulty behavior
- Mode selector

Faults Dynamics Library
Faults Behavior Library
Fault Tree Analysis

Fault Injection:

Cutsets computation:

\[ CS := \{ cs \in 2^F \mid M^X \land cs \not\models \varphi \}\]

Minimal cutsets computation:

\[ MCS := \{ cs \in CS \mid \forall cs' \in CS. cs' \subset cs \}\]

Formula representing the minimal cutsets:
Minimal Cutsets Computation

- Given an extended model $M^X := \langle V^X, I^X, T^X \rangle$, find all **minimal** Faults Configurations FC (Cutsets) s.t. $\exists$ trace $\pi$ triggering FC and witnessing $M^X \not\models \varphi$

**Example:** $CS = \{\{f_1, f_2, f_4\}, \{f_1, f_2\}\}$

**State Space**

**Not Minimal**
Minimal Cutsets Computation

Given an extended model $M^X := \langle V^X, I^X, T^X \rangle$, find all \textbf{minimal} Faults Configurations $FC$ (\textbf{Cutsets}) s.t. $\exists$ trace $\pi$ triggering FC and witnessing $M^X \not\models \varphi$

\begin{itemize}
  \item \textbf{Example:} $M^{CS} = \{\{f_1, f_2\}\}$
\end{itemize}
Fault Tree Analysis

\[ \neg \varphi \]

Single Point of Failure

\[ f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6 \]
Fault Tree Analysis
Fault Tree Analysis

\[ \neg \varphi \]

\[ f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6 \]

\[ f_2 \quad f_3 \]
Fault Tree Analysis

\[ \neg \varphi \]

\( f_1 \) \quad \( f_2 \) \quad \( f_3 \) \quad \( f_4 \) \quad \( f_5 \) \quad \( f_6 \)

\( f_2 \) \quad \( f_3 \)

Not Minimal
Fault Tree Analysis

- $\mathcal{F} := \{f_1, \ldots, f_{20}\}$
- $CS := \{\{f_1\}, \ldots, \{f_4\}, \{f_5, f_6\}, \{f_1, f_8\}, \{f_2, f_3\}\}$
- $MCS := \{\{f_1\}, \ldots, \{f_4\}, \{f_5, f_6\}\}$
- $MCS^\top := f_1 \lor f_2 \lor f_3 \lor f_4 \lor (f_5 \land f_6)$
Fault Tree Analysis

- $\mathcal{F} := \{f_1, \ldots, f_{20}\}$
- $CS := \{\{f_1\}, \ldots, \{f_4\}, \{f_5\}, \{f_1, f_8\}, \{f_2, f_3\}\}$
- $MCS := \{\{f_1\}, \ldots, \{f_4\}\}$
- $MCS^\top := f_1 \lor f_2 \lor f_3 \lor f_4 \lor (f_5 \land f_6)$
CS computation as parameter synthesis

- Parameter synthesis problem:
  - Transition system extended with parameters $X$: $\langle V, I, T, X \rangle$
    such that
    - $I$ is a formula over $V \cup X$
    - $T$ is a formula over $V \cup X \cup V'$
  - Valuation $\gamma$ of $X$ induces a transition system $M_\gamma := \langle V, \gamma(I), \gamma(T) \rangle$
  - Problem: find all $\gamma$ such that $M_\gamma \models \phi$
    - Or dually find all $\gamma$ such that $M_\gamma \not\models \phi$

- CS computation as parameter synthesis:
  - Faults $F$ as parameters
  - $M^X$ as parametric transition system
  - Find all assignments to $F$ such that $M^X_\gamma \not\models \phi$
Parameter synthesis

Start from
\( \rho = \top \)

Consider
\[ M := (V \cup U, I \land \rho, T \land \rho \land \land_{u \in U} u' = u) \]

Verify if \( M \models \phi \)

Update
\[ \rho := \rho \land \neg \text{bad} \]

Return \( \rho \)

Get counterexamples
\[ s_0(V, U), s_1(V, U), ..., s_k(V, U) \]

Compute
\[ \text{bad}(U) := \exists V. s_0(V, U) \]
Exploiting IC3 incrementality

- At each iteration:
  - $I := I \land \neg bad$
  - $T := T \land \neg bad$

- No need to restart from scratch

- IC3 can keep previous frames $F_i$

- Similarly, exploit incrementality in the underlying SAT/SMT solver
Requirements Analysis
Property correctness

- Standard problem: correctness of design against set of properties.
- Properties given as golden.
- Possible issues:
  - Properties wrongly formalized.
  - Properties may be abstract version of real requirements (to enable verification)
  - Set of properties incomplete.
- Same problems addressed by Requirements Engineering
Requirements engineering

- Old discipline (more than twenty years).
- **Goal**: precise and complete requirements.
- Many techniques on the different aspects:
  - management,
  - elicitation,
  - analysis,
  - validation.

- **Why**: errors in requirements take longer to find and correct than those inserted in later phases ⇒ higher cost
- More important in safety-critical application
Lutz in 1993 analyzed the Voyager and the Galileo software errors uncovered during integration and testing.

Half errors were safety-related, half not.

Most were functional faults: operating, conditional, or behavioral discrepancies with functional requirements.

Primary cause (62% on Voyager, 79% on Galileo) is mis-understanding the requirements.
Standard Check List

- Analysis performed with a check list.
- Manual or automatic (based on linguistic techniques) to check if requirements are (IEEE Std 830-1993)
  - Complete: define all situations
  - Consistent: no contradictory statements
  - Correct: allow all and only desired behaviors
  - Modifiable: well structured, separation of concerns
  - Ranked: prioritized according to importance
  - Testable: specified tests
  - Traceable: identifier for each statement
  - Unambiguous: only one possible interpretation
  - Valid: all stakeholders must be able to understand, analyze and accept the requirement
  - Verifiable: ability to check design against the requirement.
Formal validation loop

- Informal Requirements
- Formalization (domain expert)
- Formalized Requirements
- Analysis and refinement (domain expert)
- Verification results
- Verification (automatic engine)
Formal checks and feedback

- **Formal properties capture the semantics of requirements**
  - No model to refine the semantics of propositions
  - Requires rich property specification language
    - E.g. first-order temporal logic

- **Formal checks:**
  - **Consistency**: free of contradictions
  - **Scenario compatibility**: desired behaviors are admitted
  - **Property entailment**: undesired behaviors are not admitted
  - **Realizability**: an implementation is possible
  - **Inherent vacuity**: free of redundant/vacuous subformulas
  - **Completeness**: every situation is constrained

- **Formal feedback:**
  - **Traces**: witnesses of consistency, compatibility, property violation
  - **Cores**: subset of inconsistent, incompatible, property-entailing formulas
Reduction to Satisfiability

- Check if requirements are:
  - consistent, i.e. if they do not contain some contradiction
  - not too strict, i.e. if they do allow some desired behavior \( \psi_d \)
  - not too weak, i.e. if they rule out some undesired behavior \( \psi_u \)

- All reduced to satisfiability:
  - Consistency: \( \bigwedge_i \phi_i \)
  - Admit desired behavior: \( \bigwedge_i \phi_i \land \psi_u \)
  - Does not forbid undesired behavior: \( \bigwedge_i \phi_i \land \psi_u \)
Satisfiability procedure

- Reduce the problem to model checking
- \( \phi \) is satisfiable iff \( M_U \not\models \neg \phi \)
  - Where \( M_U \) is the universal model
- Use standard automata-theoretic approach to model checking
  - \( \phi_A \) Boolean abstraction of \( \phi \) replacing \( p(V) \) with Boolean \( v_p \)
  - \( M_\phi \) obtained from \( M_{\phi_A} \) by adding \( \land_p v_p \leftrightarrow p \)
Contract Based Design
Component-based design

- So far, system seen as monolithic behavioral model
- A **component** can be defined as a unit of composition with contractually specified interfaces
  - Hides internal information
  - Defines interface to interact with the environment
- **Component-based design** ideal for
  - Separation of concerns
  - Independent development
  - Reuse of components
- First conceived for software, now popular also for **system architectural design** (SysML, AADL, AF3, Altarica, ...)

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Specifying components with contracts

- Component hierarchically decomposed
- Requirements/properties specified at different levels of the hierarchy
- Contract: assumptions + guarantees
  - **Assumptions**: properties expected to be satisfied by the environment
  - **Guarantees**: properties expected to be satisfied by the component in response
- Correspond to pre/post conditions of standard SW contracts
Stepwise refinement

- Specify components while designing
  - decomposing the specification based on the decomposition of the architecture

- Early check of requirements
  - Ensure the correctness of the decomposition
  - Does the contract of A follow from the contracts of B and C?

- Independent refinement:
  - Based on above check, B and C can be developed independently.
Component reuse

- Library of trusted components
- Implementation + contracts
- Pluggable?
  - compare contracts!
Compositional verification
Compositional verification techniques

- Compositional verification:
  - Prove properties of the components (for example, with model checking).
  - Combine components’ properties to prove system’s property without looking into the internals of the components (sometimes reduced to validity/satisfiability check for composition of properties).

- Formally:

\[
\begin{align*}
\gamma_S(S_1, S_2, \ldots, S_n) &\models \gamma_P(P_1, P_2, \ldots, P_n) \\
\gamma_S(S_1, S_2, \ldots, S_n) &\models P
\end{align*}
\]

- \( \gamma_P \) combines the properties depending on the connections used in \( \gamma_S \)

- E.g. synchronous case:

\[
\gamma_P(P_1, P_2, \ldots, P_n) = \rho_{\gamma_S}(P_1 \land P_2 \land \ldots \land P_n)
\]

  - where \( \rho_{\gamma_S} \) is the renaming of symbols defined by the connections in \( \gamma_S \).
Contract-based compositional

- Components interact with an environment.
  - Input/output data/events
  - Input controlled by environment, output controlled by component

- May be input enabled or possibly blocking.

- Blocking an input means constraining the environment.
  - The component can be used only in some environment (assumptions!)

- Compositional rule is not just an implication!
  - Guarantees of subcomponents must be stronger
  - Assumptions of subcomponents must be weaker

- Contract-based design requires a formal definition of components’ syntax and semantics
A component interface defines boundary of the interaction between the component and its environment.

Consists of:
- Set of input and output ports (syntax)
  - Ports represent visible data and events exchanged with environment.
- Set of traces (semantics)
  - Traces as sequences of events and assignments to data ports.
Glass-box component structure

- A component has an internal structure.

**Architecture view:**
- Subcomponents
- Inter-connections
- Delegations

**State-machine view:**
- Internal state
- Internal transitions
- Language over the ports
Implementation and Environment

- $I_S$: input ports of component $S$
- $O_S$: output ports of $S$
- $V_S = I_S \cup O_S$: all ports of $S$
- Implementation/environment of $S$: transition system $\langle V, I, T \rangle$ with $V_S \subseteq V$
Composite components and connections

- Components are composed to create composite components.

- Different kind of compositions:
  - Synchronous,
  - Asynchronous,
  - Synchronizations:
    - Rendez-vous vs. buffered;
    - Pairwise, multicast, broadcast, multicast with a receiver

- Connections map (general rule of architecture languages):
  - Input ports of the composite component
  - Output ports of the subcomponents
    Into
  - Output ports of the composite component
  - Input ports of the subcomponents.
Composite components and connections

- $Sub_S$: subcomponents of $S$
- Connection
  \[ \gamma: (O_S \cup \bigcup_{S' \in Sub_S} I_{S'}) \rightarrow (I_S \cup \bigcup_{S' \in Sub_S} O_{S'}) \]
- Example:
  - $\gamma(o) = o_2$
  - $\gamma(i_2) = o_1$
  - $\gamma(i_1) = i$
Composite components and connections

- **Standard synchronous product:**
  - $M_1 = \langle V_1, I_1, T_1 \rangle$ and $M_2 = \langle V_2, I_2, T_2 \rangle$
  - $M_1 \times M_2 := \langle V_1 \cup V_2, I_1 \land I_2, T_1 \land T_2 \rangle$

- **With connection $\gamma$:**
  - $M_1 \times_\gamma M_2 := \langle \gamma(V_1 \cup V_2), \gamma(I_1 \land I_2), \gamma(T_1 \land T_2) \rangle$
  - Where
    - $\gamma(V) := \{ v | v \in V \setminus \text{dom}(\gamma) \text{ or } v = \gamma(w) \text{ for some } w \in V \}$
    - $\gamma(\phi) := \phi[v \mapsto \gamma(v)]$

- **Given implementations $M_1, \ldots, M_n$ for $Sub_S = S_1, \ldots, S_n$, and environment $E$:**
  - **Composite implementation of $S$:**
    - $M_1 \times_\gamma \ldots \times_\gamma M_n$
  - **Composite environment of $S_i$:**
    - $M_1 \times_\gamma \ldots \times_\gamma M_{j \neq i} \times_\gamma \ldots \times_\gamma M_n \times_\gamma E$
LTL contracts

- A contract of component $S$ is a pair $\langle A, G \rangle$ of LTL formulas over $V_S$
  - $A$ is the assumption
  - $G$ is the guarantee

- $Env$ is a correct environment iff $Env \models A$

- $Imp$ is a correct implementation iff $Imp \models A \rightarrow G$
Trace-based contract refinement

- The set of contracts \( \{C_i\} \) refines \( C \) with the connection \( \gamma \) \( (\{C_i\} \preceq_\gamma C) \) iff for all correct implementations \( \text{Imp}_i \) of \( C_i \) and correct environment \( \text{Env} \) of \( C \):
  1. The composition of \( \{\text{Imp}_i\} \) is a correct implementation of \( C \).
  2. For all \( k \), the composition of \( \text{Env} \) and \( \{\text{Imp}_i\}_{i \neq k} \) is a correct environment of \( C_k \).

- Verification problem:
  - check if a given refinement is correct (independently from implementations).

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Proof obligations for contract refinement

- Given $C_1 = \langle \alpha_1, \beta_1 \rangle, \ldots, C_n = \langle \alpha_n, \beta_n \rangle, C = \langle \alpha, \beta \rangle$
- Proof obligations for $\{C_i\} \preceq C$:
  - $\forall \left((\forall 1 \leq j \leq n (\alpha_j \rightarrow \beta_j)) \rightarrow (\alpha \rightarrow \beta)\right)$
  - $\forall \left((\forall 2 \leq j \leq n (\alpha_j \rightarrow \beta_j)) \rightarrow (\alpha \rightarrow \alpha_1)\right)$
  - ...
  - $\forall \left((\forall 1 \leq j \leq n, j \neq i (\alpha_j \rightarrow \beta_j)) \rightarrow (\alpha \rightarrow \alpha_i)\right)$
  - ...
  - $\forall \left((\forall 1 \leq j \leq n-1 (\alpha_j \rightarrow \beta_j)) \rightarrow (\alpha \rightarrow \alpha_n)\right)$

- Theorem: $\{C_i\} \preceq \gamma C$ iff the proof obligations are valid. [CT12]
Assume-guarantee reasoning

- Correspond to one direction of the contract refinement.
- Many works focused on finding the right assumption/guarantee.
- E.g. how to break circularity?
  - \((G(A \rightarrow B) \land G(B \rightarrow A)) \Rightarrow G(A \land B)\) is false
  - Induction-based mechanisms
    \((B \land G(A \rightarrow XB) \land A \land G(B \rightarrowXA)) \Rightarrow G(A \land B)\) is true
Contract Based Safety Assessment
Contract-Based Safety Assessment

- “Monolithic” safety assessment artifacts e.g., minimal cutsets, might be not easily understandable
- Need for more structured safety artifacts e.g., hierarchically organized fault trees
- Leverage the architectural decomposition of contract-based design
- Perform automated Safety Assessment on a Contract-Based system decomposition
Formal Verification, Validation, and Safety Assessment

Monolithic

Veriﬁcation & Validation

Composition

Model Checking

Fault Injection

Model-Based Safety Assessment

\[ M \models \varphi \]

\[ M \xrightarrow{\delta(F)} M^X \]

\[ M^X \not\models \varphi \]
Formal Verification, Validation, and Safety Assessment

Contract-Based Design

Monolithic

Model Checking

\( M \models \varphi \)

Compositional

Fault Injection

\( M \Rightarrow M^X \)

Model-Based Safety Assessment

\( \delta(F) : M^X \not\models \varphi \)

Verification & Validation

Safety Assessment
Formal Verification, Validation, and Safety Assessment

**Contract-Based Design**

**Contract-Based Fault Injection**

**Model Checking**

\[ M \models \varphi \]

**Fault Injection**

\[ M \implies M^X \]

**Model-Based Safety Assessment**

\[ \delta(F) : M^X \not\models \varphi \]

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Formal Verification, Validation, and Safety Assessment

Monolithic

Monolithic Verification & Validation

Compositional

Compositional Contract-Based Design

Compositional Contract-Based Fault Injection

Compositional Contract-Based Safety Assessment

Model Checking

Model Checking $\mathcal{M} \models \varphi$

Fault Injection

Fault Injection $\mathcal{M} \boxright \mathcal{M}^X$

Model-Based Safety Assessment

Model-Based Safety Assessment $\delta(\mathcal{F}) : \mathcal{M}^X \not\models \varphi$

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Contract-Based Safety Assessment
Contract-Based Safety Assessment

- Extension of contracts (fault injection) from a Contract-Based decomposition
Contract-Based Safety Assessment

- Extension of contracts (fault injection) from a Contract-Based decomposition
- Automated Formal Safety Assessment i.e., Fault Tree Analysis

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Contract-Based Safety Assessment

- Extension of contracts (fault injection) from a Contract-Based decomposition
- Automated Formal Safety Assessment i.e., Fault Tree Analysis
- Support for components refinement
Contract-Based Fault Injection

\[ \langle A, G \rangle \]
Contract-Based Fault Injection

\[ \langle A, G \rangle \quad \rightarrow \quad \langle A^X, G^X \rangle := \langle \neg f^I \rightarrow A, \neg f^O \rightarrow G \rangle \]

- Additional input and output failure ports
- Contract extension
Contract-Based Fault Injection

• Additional input and output failure ports
• Contract extension
Contract-Based Fault Injection

\[ \langle A, G \rangle \implies \langle A^X, G^X \rangle := \langle \neg f^I \rightarrow A, \neg f^O \rightarrow G \rangle \]

- Additional input and output failure ports
- **Contract extension**
Starlight Example

[Diagram of a Starlight example with labeled components: H, E, D, L, M, U, and arrows indicating connections and signals such as res, cmdH, fwH, cmdL, resL, cmd, switch, and return.]
Starlight reqs formalization

- **Req-Sys-secure**: No high-level data shall be sent by L to the external world.
  - **Formal-Sys-secure**: never is_high(last_data(outL))

- **Req-User-secure**: The user shall switch the dispatcher to high before entering high-level data.
  - **Formal-User-secure**: always
    
    $$((\text{is\_high}(\text{last\_data}(\text{cmd}))) \implies ((\text{not} \text{ switch\_to\_low}) \text{ since switch\_to\_high}))$$

- **Proved system guarantess Formal-Sys-secure assuming Formal-User-secure.**

- **Req-Sys-safe**: No single failure shall cause a loss of Req-Sys-secure.
Starlight fault tree for secure req
Case-Studies
AIR6110 Wheel Braking System

- Joint scientific study with Boeing

- Context
  - Aerospace systems become more complex and integrated
  - Safety assessment process is critical
    - Evaluate whether a selected design is sufficiently robust with respect to the criticality of the system and faults occurrence

- Objectives:
  - Analyze the system safety through mathematical models and techniques
  - Demonstrate the usefulness and suitability of these techniques for improving the overall traditional development and supporting aircraft certification

- Case study:
  - Aerospace Information Report 6110:
    - Traditional Contiguous Aircraft/System Development Process Example
  - Wheel Brake System of a fictional dual-engine aircraft
    - 300-350 passengers, 5h max of flight
    - 2 main landing gears (4 wheels each)
WBS: Overview
WBS: Adopted approach

MODELING

Architecture decomposition & Contracts
ocra language

V & V

• Automatic contract refinement verification

OCRA

• Automatic compositional verification

OCRA

• Automatic monolithic verification

nuXmv

M ⊨ \varphi

MASS

Fault extension

• Automatic fault extension

OCRA

• Automatic hierarchical fault tree generation

OCRA

Safety Assessment

Fault trees computation

• Over-approximation

• Failure modes defined by the user

OCRA

• Generation of the extended system implementation

xSAP

M \rightsquigarrow M[F]

\delta(F) : M[F] \not\models \varphi

Behavioral Implementation
(Leaf components & System)

smv language

Semi-automatic Generation

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WBS: Conclusion

Results:
- Cover the process described in AIR6110 with formal methods
- Production of modular descriptions of 5 architectures variants
  - Analysis of their characteristics in terms of a set of requirements expressed as properties
  - Production of more than 3000 fault trees
  - Production of reliability measures
- Detection of an unexpected flaw in the process
  - Detection of the wrong position of the accumulator earlier in the process

Lessons learned:
- Going from informal to formal allows highlighting the missing information of the AIR6110 to reproduce the process
- OCRA modular modeling allows a massive reuse of the design through architectures variant
- Automated and efficient engines as IC3 is a key factor
- MBSA is crucial in this context:
  - Automatic extension of the nominal model with faults
  - Automatic generation of artifacts eases the analysis and the architecture comparison in terms of safety
NASA NextGen Air Traffic Control

- Problem:
  - 4x airspace traffic in the next 20 years
  - Currently technology cannot scale
  - Need to increase automation, while preserving safety

- Apply Formal Methods to study the quality and Safety of many design proposals concerning the allocation of tasks between Air and Ground

- Objective:
  - Highlight Implicit assumptions
  - Model and Study a design space with more than 1600 proposals
  - Time-Frame: 12 Man-Month

- Joint project with NASA Ames and Langley
NextGen: Proposed Solution

- Identify dimensions of the design space
- Use a parametric model to encode all designs (symbolically)
- Unified design architecture makes it possible to push complexity into the leaf components
- Use contracts to validate components behavior
- Perform Model-Checking against interesting properties, and rank solutions based on their "quality"
- Perform Fault-Tree analysis to understand the resilience to faults
NextGen: Results

- Independently reproduced 2 known problems
- Highlighted a mismatch in requirements for one design proposal
- Results discussed and validated by NASA engineers

Lessons Learned:
- Model Validation is an key step
- Technology is mature to tackle problems of this size
- Lots of data: Need better ways to present complex results in an accessible way
Wrap-up
Lecture Summary

- Importance of Safety Assessment
- Contract-Based Design
  - Specify & Validate Requirement
  - Decompose Requirements onto Architecture
  - Implement Leaf components
  - Functional correctness guaranteed by Contract-Decomposition
- CBSA: Leverage contracts to perform Safety Assessment
Readings

A list of suggested readings on the topics of the course. The list is not meant to be complete.

- **Model-Based Safety Assessment:**
  - Marco Bozzano, Alessandro Cimatti, Alberto Griggio, Cristian Mattarei: Efficient Anytime Techniques for Model-Based Safety Analysis. CAV (1) 2015: 603-621

- **Parameter Synthesis:**
  - Alessandro Cimatti, Alberto Griggio, Sergio Mover, Stefano Tonetta: Parameter synthesis with IC3. FMCAD 2013: 165-168
Readings

- Requirements Formalization and Validation:
  - Alessandro Cimatti, Marco Roveri, Stefano Tonetta: Requirements Validation for Hybrid Systems. CAV 2009: 188-203

- Compositional Verification:
  - Kenneth L. McMillan: Circular Compositional Reasoning about Liveness. CHARME 1999: 342-345
  - Anvesh Komuravelli, Nikolaj Bjørner, Arie Gurfinkel, Kenneth L. McMillan: Compositional Verification of Procedural Programs using Horn Clauses over Integers and Arrays. FMCAD 2015: 89-96
Readings

- **Contract-Based Design with Temporal Logics:**

  - Alessandro Cimatti, Stefano Tonetta: A Property-Based Proof System for Contract-Based Design. EUROMICRO-SEAA 2012: 21-28


  - Alessandro Cimatti, Ramiro Demasi, Stefano Tonetta: Tightening a Contract Refinement. SEFM 2016

Readings

- **Contract-Based Safety Assessment:**

- **Case Studies:**

- **Tools used in the course:**
  - Alessandro Cimatti, Michele Dorigatti, Stefano Tonetta: OCRA: A tool for checking the refinement of temporal contracts. ASE 2013: 702-705
  - Roberto Cavada, Alessandro Cimatti, Michele Dorigatti, Alberto Griggio, Alessandro Mariotti, Andrea Micheli, Sergio Mover, Marco Roveri, Stefano Tonetta: The nuXmv Symbolic Model Checker. CAV 2014: 334-342
  - Benjamin Bittner, Marco Bozzano, Roberto Cavada, Alessandro Cimatti, Marco Gario, Alberto Griggio, Cristian Mattarei, Andrea Micheli, Gianni Zampedri: The xSAP Safety Analysis Platform. TACAS 2016: 533-539