Engineering Dependable Software Systems

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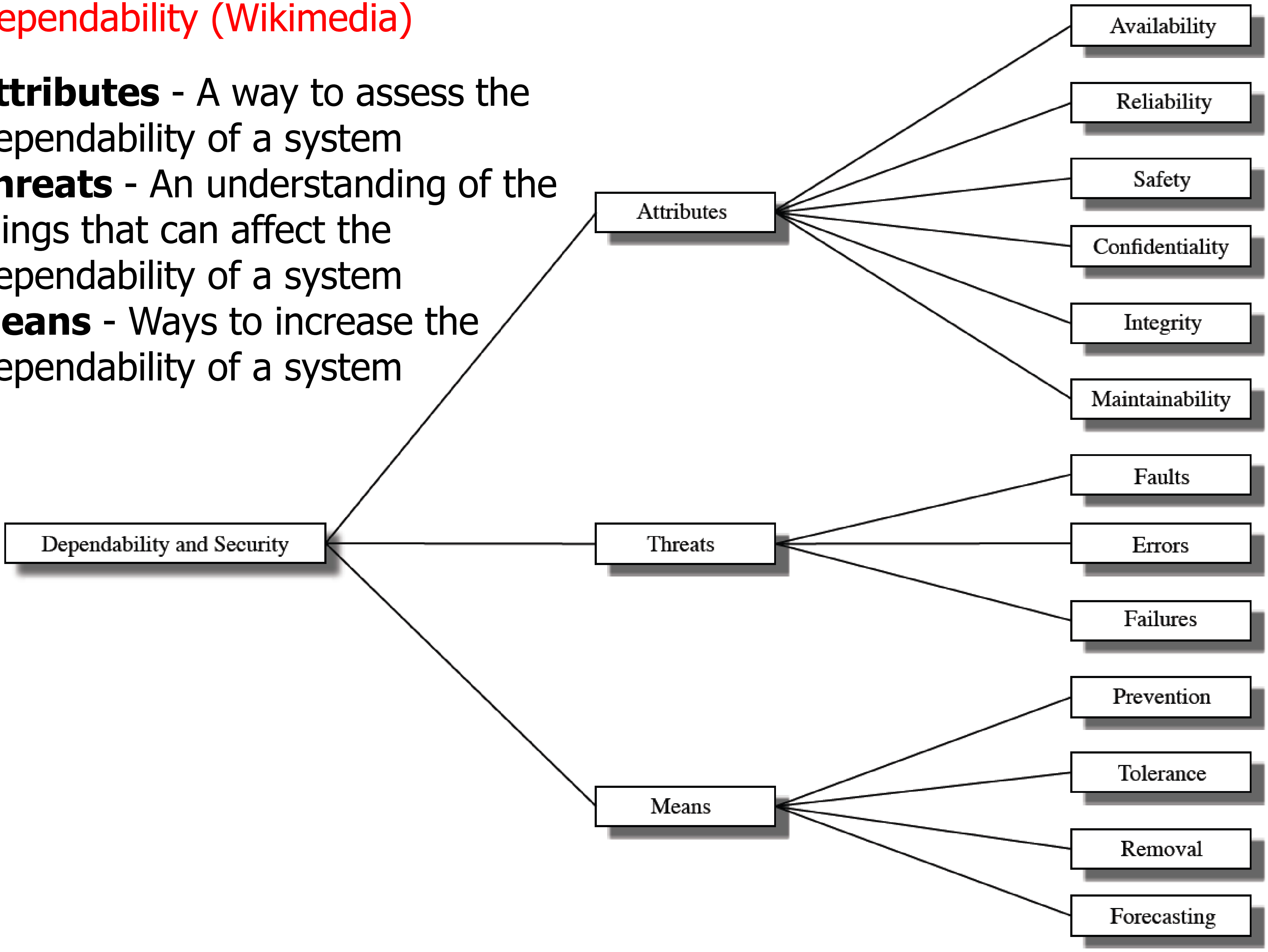
Dependability (Wikimedia)

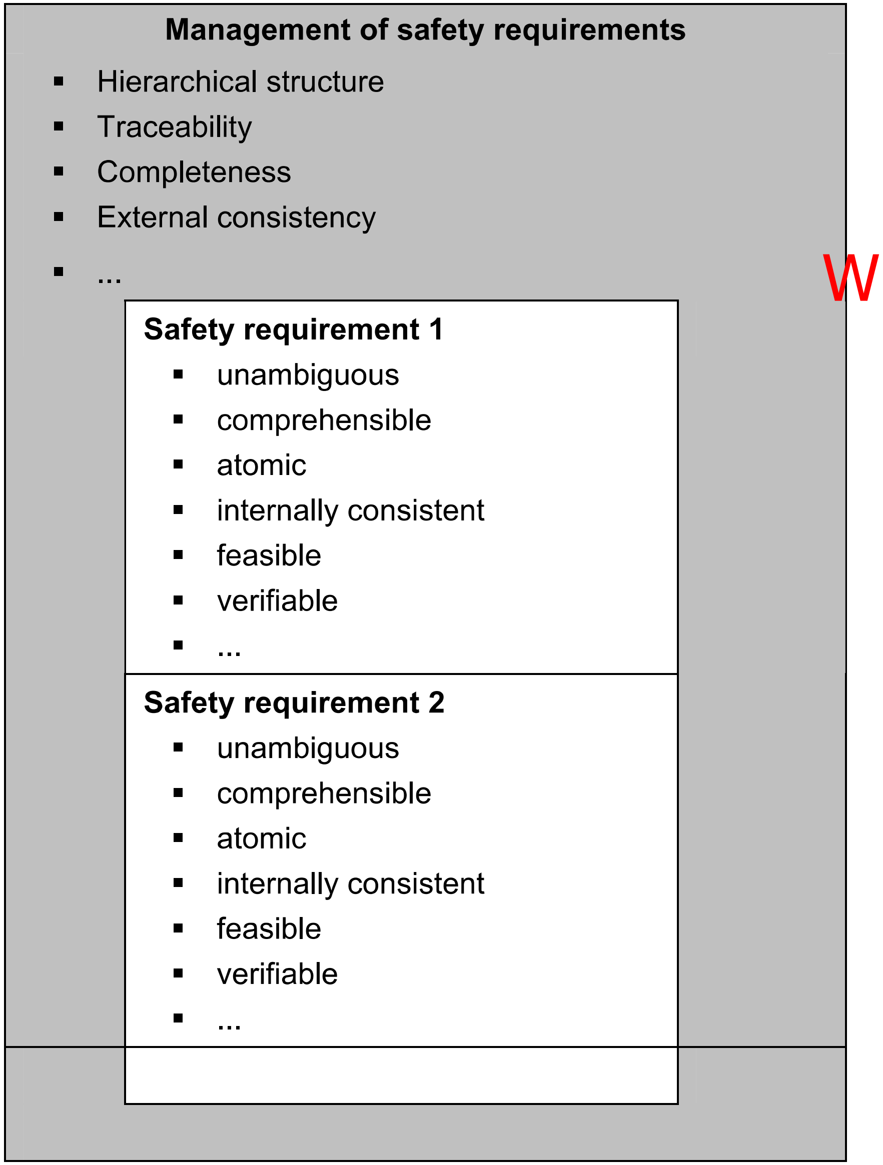
Attributes - A way to assess the Dependability of a system

Threats - An understanding of the things that can affect the Dependability of a system

Means - Ways to increase the Dependability of a system



Traceability Use Case: ISO 26262 – Functional Safety



Management of safety requirements

- Hierarchical structure
- Traceability
- Completeness
- External consistency
- ...

Safety requirement 1

- unambiguous
- comprehensible
- atomic
- internally consistent
- feasible
- verifiable
- ...

Safety requirement 2

- unambiguous
- comprehensible
- atomic
- internally consistent
- feasible
- verifiable
- ...

What is functional safety?

Traceability Use Case: ISO 26262 – Functional Safety

- The management of safety requirements includes
  - ◊ managing requirements,
  - ◊ obtaining agreement on the requirements,
  - ◊ obtaining commitments with those implementing the requirements, and
  - ◊ maintaining traceability
- During the development of the software architectural design the following shall be considered:
  - ◊ a) the verifiability of the software architectural design;
    NOTE This implies bi-directional traceability.
- The software unit design and implementation shall be verified in accordance with ISO 26262-8:
  - ◊ b) the completeness regarding the software safety requirements and the software architecture through traceability;

A Logical Approach to Systems Engineering Artifacts and Traceability: **From Requirements to Functional and Architectural Views**

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Content and Motivation

- Presentation of key artifacts in systems engineering in logic
  - ◊ Assertions about the system
- System models and their representation in logic
  - ◊ Interfaces
  - ◊ Architectures
- Key artifacts in systems engineering
  - ◊ System level requirements
  - ◊ Functional specification
  - ◊ Architecture
- Concepts relating assertions: logical dependence relations
- Concepts for relating artifacts
  - ◊ Understanding the logical dependencies between artifacts
  - ◊ Traceability: Intra- and inter-artifact links and traces

Assertions

Assertions

- A logical predicate p over a universe D is a mapping

  $$p: D \to \mathbb{B}$$

  where D is a mathematical set also called the universe of discourse.

- Often the elements $d \in D$ can be characterized by a set of attributes

  $$x_i: D \to T_i \qquad \text{for} \qquad 1 \le i \le n$$

  where
  T_i are the (data) types for these attributes and
  n is the number of attributes.

Example: Assertions

- For a simple universe of discourse Car representing cars, consider attributes such as

  $\text{length}: \text{Car} \to \text{IN}$

  $\text{number\_of\_seats}: \text{Car} \to \text{IN}$

  $\text{speed}: \text{Car} \to \text{IN}$

  $\text{situation}: \text{Car} \to \{\text{city}, \text{country}, \text{high\_way}\}$

- Based on the attributes, given $d \in \text{Car}$, we write logical expressions such as

  $$\text{speed}(d) \geq 50 \wedge \text{situation}(d) = \text{city}$$

- This notation can be simplified for a fixed car d:

  $$\text{speed} \geq 50 \wedge \text{situation} = \text{city}$$

- Such a logical expression referring to the attributes of the elements of the considered universe is called *assertion*.

Typing attributes

- In an assertion like

$$speed \geq 50 \wedge situation = city$$

the attributes have types.

- Sometimes it is useful to indicate the types of attributes explicitly

$$(speed: IN, situation: \{city, country, high\_way\}): \\ speed \geq 50 \wedge situation = city$$

Notation

- For assertions Q the following shorthand notation is used:

$\forall X{:}Q$ for $\forall\ x_1, \dots, x_n{:}\ Q$

$\exists X{:}Q$ for $\exists\ x_1, \dots, x_n{:}\ Q$

where $X = \{x_1, \dots, x_n\}$ are free variables in Q

$\forall Q$ iff $Q \equiv \text{true}$ e.g. $\forall\ x_1, \dots, x_n{:}\ Q$

where $x_1, \dots, x_n$ are all the free variables in Q

$\exists Q$ iff $\neg\forall\neg Q$

Language of assertions

- Given a signature Σ of attributes by

  $$LA(\Sigma)$$

  we denote the assertion language over signature Σ which is the set of assertions that can be formulated over signature Σ.
- Assertions are Boolean expresses and therefore all the logical operators can be applied to them

Formalizing Domains

From the informal to the formal

- In the beginning, properties of the universe are formulated in natural language, in general

  "The airbag is activated within 200 msec whenever the crash sensor indicates a crash"

- The step to the formal means
  - ◊ Derivation of a "data" model: Introducing a set of attributes
  - ◊ Capturing properties by assertions in terms of these attributes
- This step into formalization has two aspects
  - ◊ Abstraction: the attributes can only address a limited set of properties
  - ◊ Precision: informal properties are made precise

    This includes
    - Decisions: there are usually several ways to make an informal property precise

Assertions about Systems

- Assertions and languages of assertions can be built for many different universes – problem domains
  Examples:
  - ◊ Airplanes
  - ◊ Medical devices
  - ◊ Cars
  - ◊ Banking
  - ◊ …
- We are aiming at assertion languages for systems with emphasis on software systems and systems with embedded software

Remark: difference between assertions and propositions

- An assertion P defines a property
  - ◊ By the attributes P it formulates a property about a system

    $situation = city \Rightarrow speed \leq 50$
  - ◊ A car may have this property or not
- A proposition is either true or false
  - ◊ It either holds or not

    $\forall(situation = city \Rightarrow speed \leq 50)$
  - ◊ This proposition is true if the specified property is true for all cars

Remark: difference between axioms and specifications

- Using an assertion P as a specification means that P specifies a property that is required for the system under development
  - ◊ By the attributes in P it formulates a specification about systems

    situation = city ⇒ speed ≤ 50
  - ◊ A car may fulfill this specification or not
- An axiom is an assertion P that states a property about all systems
  - ◊ It holds for all systems

    ∀(speed ≤ 500)
  - ◊ Then P is a trivial specification

Note: The axioms describe the universe of systems under consideration, the assumptions about the considered universe of systems – they form the problem domain theory

Artifacts - Structure and Content

System Development

- In systems development typically a large number of descriptions and statements about systems are worked out
- This information is captured in documents we call artifacts
- Examples of artifacts
  - ◊ List of requirements
  - ◊ Architectures description
  - ◊ Code listings
  - ◊ Collection of test cases
  - ◊ …

Artifacts - Structure and Content

- An *artifact* is a development document
- An *artifact* has structure and content
- An artifact contains content that is structured into
  - ◊ (finite) sets of content chunks as well as
  - ◊ finite sets of finite sets of content chunks and so on.
- This way we get nested sets of content chunks forming content hierarchies.
- Typically content chunks are informal statements of assertions about the system under development (or more generally, its development process etc.)

Illustrating Examples: Content Chunks

- System level requirements (functional requirements)

  “the car must not increase its speed without user’s control”

- System level functional specification

  “the function acc (adaptive cruise control) accelerates the car up to the speed selected by the user, provided no obstacles are recognized in front”

- Architecture specification

  “the radar signal based sensor measures the distance to the car in front and sends it to the acc monitor every 100 ms”

From content chunks to assertions

- To go from content chunks such as

  "the car must not increase its speed without user's control"

  "the function acc (adaptive cruise control) accelerates the car up to the speed selected by the user, provided no obstacles are recognized in front"

  needs modeling and formalization.

This involves the following steps

- Formalizing the elements of the universe – elicitation of the problem domain
  - ◊ Selecting the attributes
  - ◊ Defining basic propositions (called the problem domain theory)

    $\forall(\text{speed} \leq 500)$
- Expressing the informal statement by an assertion

Observation about the step of formalization

- The problem domain model has to be chosen in a way, that the informal statement can be captured
  - ◊ "Expressiveness"
  - ◊ This may require sophisticated models (talking about time, space, interaction, reaction, intension, …)
- There might be several ways to formalize an informal statement
  - ◊ Eliminating linguistic ambiguity
- Usually it is not a good idea that all content chunks are formalized

Given two assertions P and Q;
what does logical dependency mean?

Relating Assertions

Relating Assertions to Assertions - Implication

- Two assertions

$$P, Q$$

are in an *implication* relation if

$$\forall(P \Rightarrow Q)$$

or vice versa

$$\forall(Q \Rightarrow P)$$

- Related relations are

$$\forall(\neg Q \Rightarrow P)$$

or

$$\forall(P \Rightarrow \neg Q)$$

Negating the independence conditions

Condition	Negation	Result	Result	Result
$(PÙQ)	Ø$(PÙQ)	" Ø(PÙQ)	" (ØPÚØQ)	" (PÞ ØQ)
$(ØPÙQ)	Ø$(ØPÙQ)	" Ø(ØPÙQ)	" (PÚØQ)	" (QÞ P)
$(PÙØQ)	Ø$(PÙØQ)	" Ø(PÙØQ)	" (ØPÚQ)	" (PÞ Q)
$(ØPÙØQ)	Ø$(ØPÙØQ)	" Ø(ØPÙØQ)	" (PÚQ)	" (ØPÞ Q)

D.H. Sanford: Independent Predicates. American Philosophical Quarterly 18:2, 1981, 171-174

Relating Assertions – Logical Independency

If every of the following four relations

$$\exists(P \wedge Q)$$
$$\exists(\neg P \wedge Q)$$
$$\exists(P \wedge \neg Q)$$
$$\exists(\neg P \wedge \neg Q)$$

holds then we call assertions P and Q *logically independent.*

Example: Independence

- Consider the following assertions

  P: situation = city

  Q: speed ≤ 50

- Whether these assertion are independent depends on the problem domain theory
  - ◊ If we assume (as part of the problem domain theory)

    $\forall$(situation = city ⇒ speed ≤ 50)

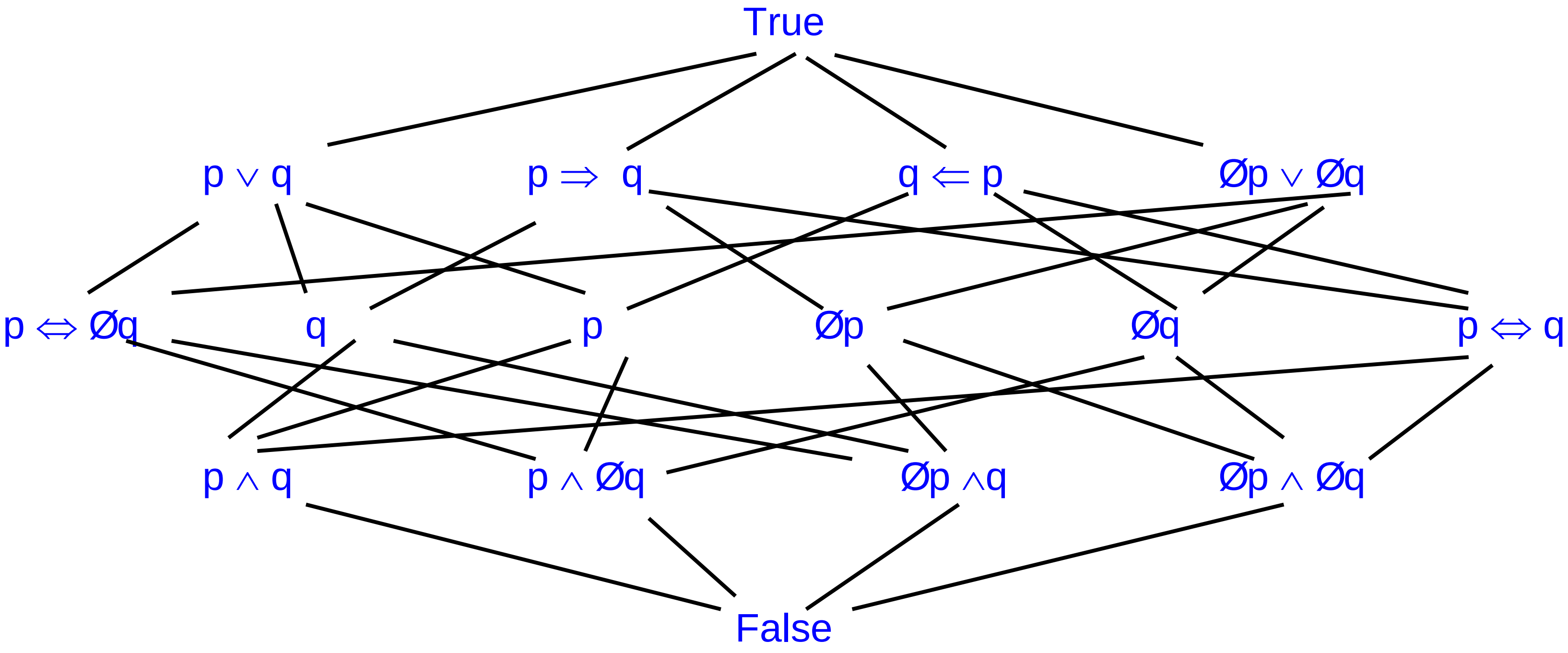
    P and Q are not independent
  - ◊ If we assume no properties as part of the problem domain theory) P and Q are independent

The Cases of Dependence

Tab. Logical Consequences of Negations of the Conditions of Logical Independence

$p∧q	$p∧Øq	$Øp∧q	$Øp∧Øq	Implies	consequence
True	True	True	True	True	independence
True	True	True	False	" d: p(d) ∨ q(d)	unavoidance
True	True	False	True	" d: p(d) ⇐ q(d)	implication
True	True	False	False	" d: q(d)	implication, unavoidance
True	False	True	True	" d: p(d) ⇒ q(d)	implication
True	False	True	False	" d: p(d)	implication, unavoidance
True	False	False	True	" d: p(d) ⇔ q(d)	equivalence
True	False	False	False	" d: p(d) ∧ q(d)	p and q tautologies
False	True	True	True	" d: Øp(d) ∨ Øq(d)	mutual exclusion
False	True	True	False	" d: p(d) ⇔ Øq(d)	antivalence
False	True	False	True	" d: Øq(d)	implication, mutual exclusion
False	True	False	False	" d: Øp(d) ∧ q(d)	implication, mutual exclusion, unavoidance
False	False	True	True	" d: Øp(d)	implication, mutual exclusion
False	False	True	False	" d: p(d) ∧ Øq(d)	implication,
False	False	False	True	" d: Øp(d) ∧ Øq(d)	Øp and Øq tautologies
False	False	False	False	False	inconsistency

The Lattice of Dependence



True

p ∨ q

p ⇒ q

q ⇐ p

Øp ∨ Øq

p ⇔ Øq

q

p

Øp

Øq

p ⇔ q

p ∧ q

p ∧ Øq

Øp ∧q

Øp ∧ Øq

False

Inconsistency

- Assertions P and Q are called *inconsistent* if

  $$\neg\exists(P \wedge Q)$$

- If assertions P and Q are inconsistent, then both propositions

  $$\forall(P \Rightarrow \neg Q)$$

  $$\forall(Q \Rightarrow \neg P)$$

  hold, i.e. they are logically dependent.

Logical Overlap

- Two assertions P and Q are called *logically overlapping* iff

  $$\neg\forall(P\lor Q)$$

  which is equivalent to the statement,

  $$\exists(\neg P\land\neg Q)$$

- Then there is a non-trivial property R
  - ◊ (nontrivial means that $\neg\forall R$ holds)
  - ◊ that is implied both by assertion P and by assertion Q; i.e.

  $$\forall(P \Rightarrow R) \text{ and } \forall(Q \Rightarrow R)$$

- We choose the strongest assertion R
  - ◊ that is implied both by assertion P and by assertion Q as follows:

  $$R = P\lor Q$$

- Property R is not trivially true (i.e. $\exists\neg R$) iff assertions P and Q are overlapping.

Logical Overlap

- Not overlapping assertions are logically not independent, since

$$\forall(P \vee Q)$$

which transforms to

$$\neg\exists(\neg P \wedge \neg Q)$$

and to

$$\forall(\neg P \Rightarrow Q)$$

$$\forall(\neg Q \Rightarrow P)$$

- In other terms, independent assertions are always overlapping.

Example: overlapping assertions

- The assertions:

  P: speed $\leq$ 100

  Q: speed $\geq$ 50

  are not overlapping:

  $\forall$(speed $\leq$ 100 $\vee$ speed $\geq$ 50)

- The assertions:

  P: speed $\geq$ 100

  Q: speed $\leq$ 50

  are overlapping:

  $\neg\forall$(speed $\geq$ 100 $\vee$ speed $\leq$ 50)

  $\exists$(speed $\leq$ 100 $\wedge$ speed $\geq$ 50)

Negating the independence conditions

Condition	Negation	Result	Result	Result
$(PÙQ)	Ø$(PÙQ)	" Ø(PÙQ)	" (ØPÚØQ)	" (PÞ ØQ)
$(ØPÙQ)	Ø$(ØPÙQ)	" Ø(ØPÙQ)	" (PÚØQ)	" (QÞ P)
$(PÙØQ)	Ø$(PÙØQ)	" Ø(PÙØQ)	" (ØPÚQ)	" (PÞ Q)
$(ØPÙØQ)	Ø$(ØPÙØQ)	" Ø(ØPÙØQ)	" (PÚQ)	" (ØPÞ Q)

D.H. Sanford: Independent Predicates. American Philosophical Quarterly 18:2, 1981, 171-174

System Properties at Different Levels of Abstractions: Relating Views

Example: Relating Levels of Abstraction

Logical_level

…

crash ⇒ air_bag

…

Technical_level

…

crash_sensor ⇒
activate_air_bag

…

Example: Relating Levels of Abstraction

Logical_level

…

crash ⇒ air_bag

…

Technical_level

…

crash_sensor ⇒
activate_air_bag

…

Translator

…

crash ⇔ crash_sensor

air_bag ⇔ activate_air_bag

…

Translators between Levels of Abstractions

- A specification given by a set $S_1 \subseteq LA(\Sigma_1)$ of assertions over some attribute signature Σ_1

is translated into

- a specification $S_2 \subseteq LA(\Sigma_2)$ over some attribute signature Σ_2
  - ◊ where signatures Σ_1 and Σ_2 only partially overlap or are disjoint
- by a set T of assertions formulated over signatures Σ_1 and Σ_2.

Translators between Levels of Abstractions

For a translation we require that for every assertion

$$a_1 \in LA(\Sigma_1)$$

over signature Σ_1 there exists an assertion

$$a_2 \in LA(\Sigma_2)$$

over Σ_2 such that the following formula is valid:

$$(\wedge T) \Rightarrow (a_1 \Leftrightarrow a_2)$$

- Then the set T is called a *translator from signature* Σ_1 *to signature* Σ_2.
- A set S_1 of assertions is called a *refinement* of a set S_2 of assertions according to translator T if

$$(\wedge T) \wedge (\wedge S_1) \Rightarrow \wedge S_2$$

Translators between Levels of Abstractions

- If T is free of contradictions T is called *consistent translator*.
- If for every assertion $a_1 \in LA(\Sigma_1)$ and every set S_1 of assertions formulated over signature Σ_1 and for every assertion $a_2 \in LA(\Sigma_2)$ and every set S_2 of assertions formulated over signature Σ_2

$$[(\wedge T) \wedge (\wedge S_1) \Rightarrow a_1] \Leftrightarrow [(\wedge S_1) \Rightarrow a_1]$$

$$[(\wedge T) \wedge (\wedge S_2) \Rightarrow a_2] \Leftrightarrow [(\wedge S_2) \Rightarrow a_2]$$

T is called *unbiased translator between signatures* Σ_1 *and* Σ_2.

Why translators are useful?

- Translators relate logical assertions to technical/physical assertions
- They force to make explicit assumptions behind physical/technical designs
  - ◊ As part of specifications
  - ◊ To validate them – to discover invalid assumptions

Goal:
Description of views of systems as captured by artifacts by sets of assertions

Logical Basis: Specifying Systems by Assertions

A slide due to Michael Jackson

An industrial press system

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mac

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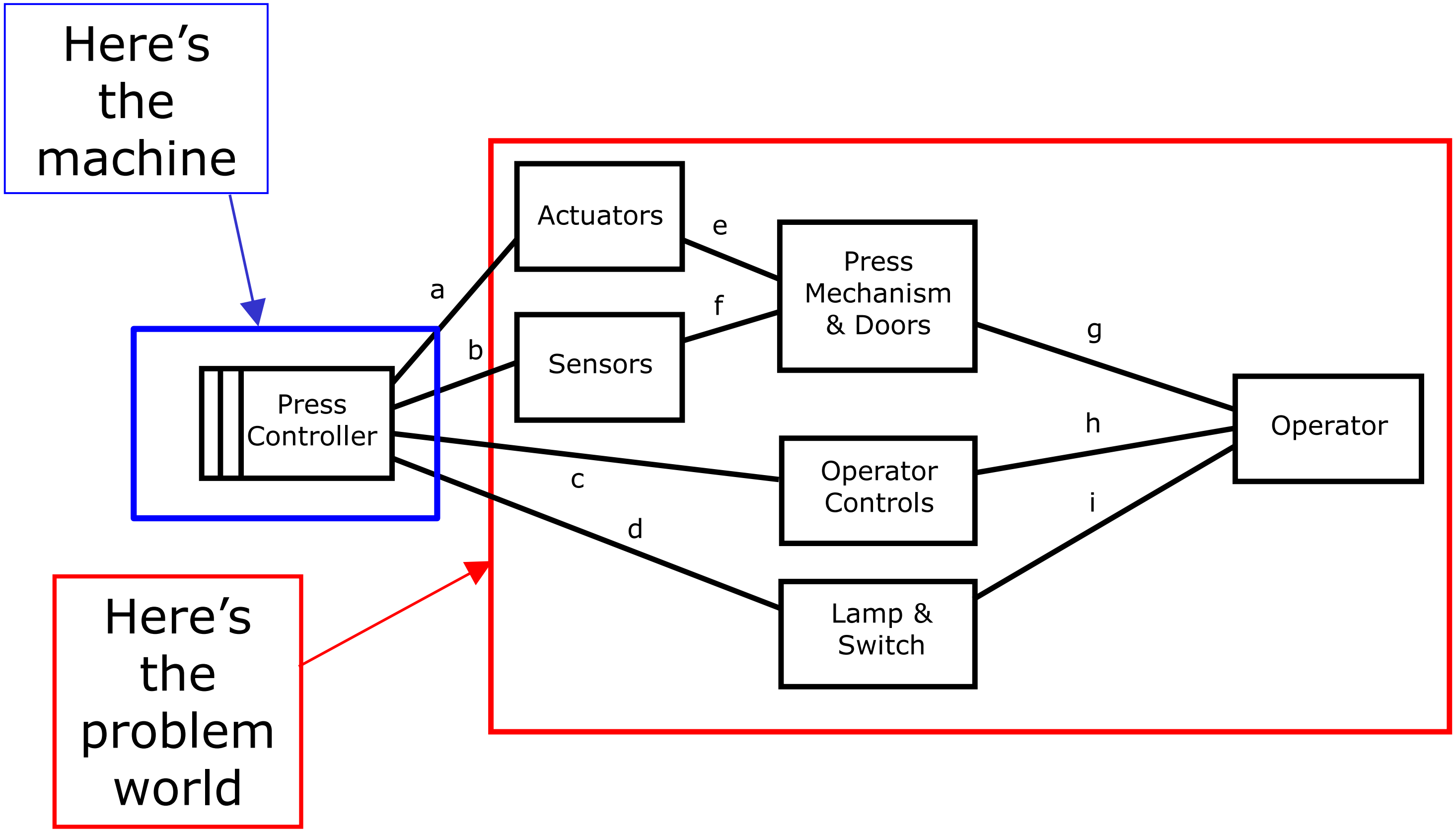
What is
a system?

A slide due to Michael Jackson

An industrial press system



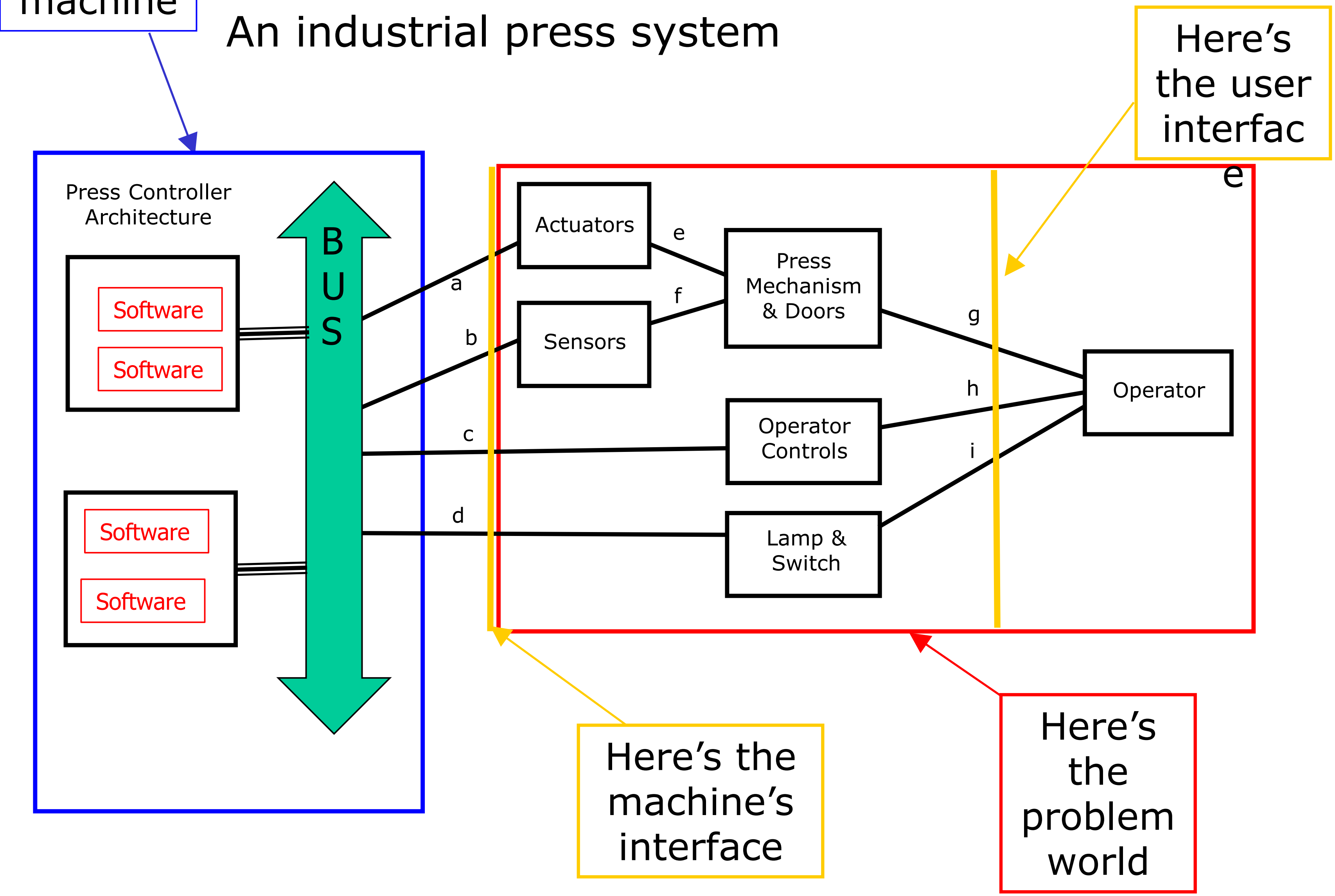
Here’s the machine

Here’s the problem world

Extending a slide due to Michael Jackson

Here's the machine

An industrial press system

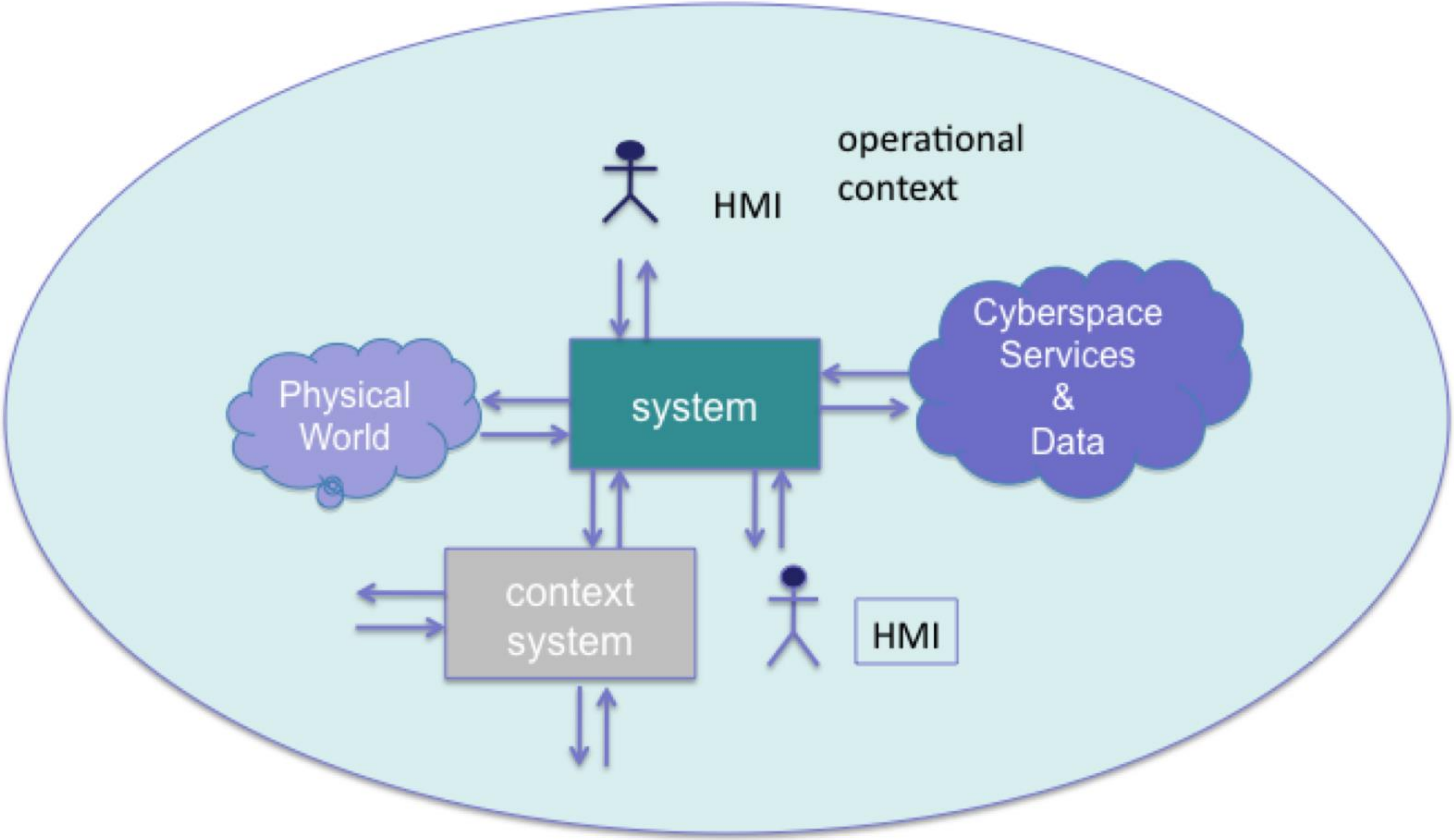


Here's the user interfac e

Here's the machine's interface

Here's the problem world

System and its context



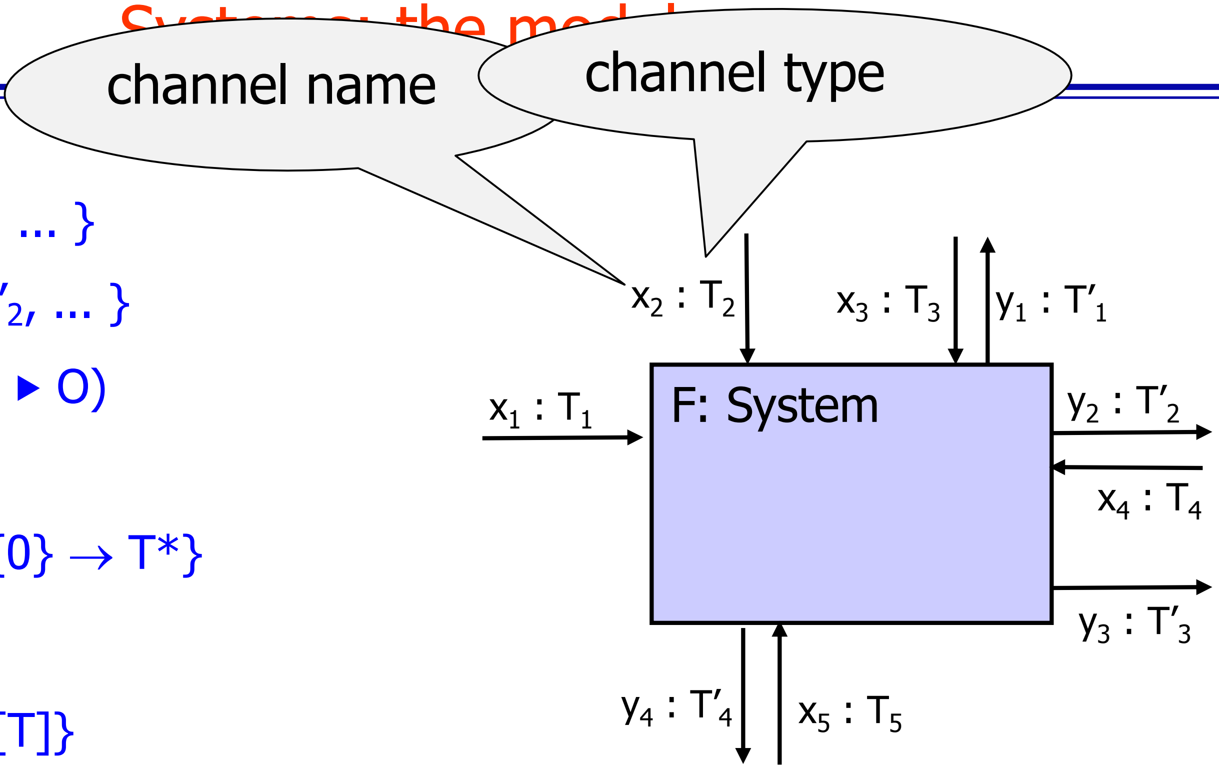
Basic System Notion: What is a discrete system (model)

A system has

- a system boundary that determines
  - what is part of the systems and
  - what lies outside (called its context)
- an interface (determined by the system boundary), which determines,
  - what ways of interaction (actions) between the system und its context are possible (static or syntactic interface)
  - which behavior the system shows from view of the context (interface behavior, dynamic interface, interaction view)
- a structure and distribution with an internal structure, given
  - by its structuring in sub-systems (sub-system architecture)
  - by its states und state transitions (state view, state machines)
- quality profile
- the views use a data model
- the views may be documented by adequate models

Interfaces

Systems: the model



Sets of typed channels

$I = \{x_1 : T_1, x_2 : T_2, \ldots\}$

$O = \{y_1 : T'_1, y_2 : T'_2, \ldots\}$

syntactic interface $(I \blacktriangleright O)$

data stream of type T

$\mathrm{STREAM}[T] = \{\mathbb{N}\backslash\{0\} \to T^*\}$

valuation of channel set C

$\vec{C} = \{C \to \mathrm{STREAM}[T]\}$

interface behavior for syn. interface $(I \blacktriangleright O)$

$[I \blacktriangleright O] = \{\vec{I} \to \wp(\vec{O})\}$

interface specification

$p: I \cup O \to \mathbb{B}$

represented as interface assertion S - logical formulae with channel names as attributes of type stream

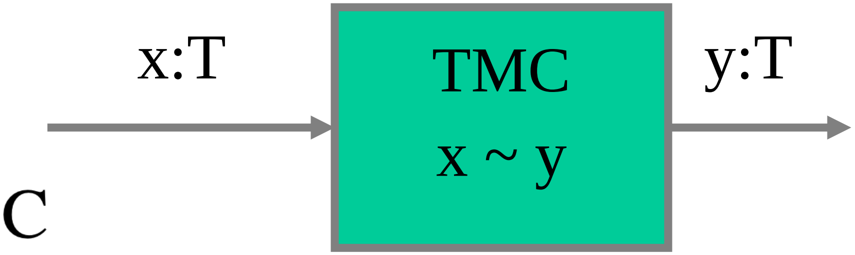
System Specification by Interface Assertions

Interface Assertion

- Given a syntactic interface (I▸O) with
  - ◊ a set I of typed input channels and
  - ◊ a set O of typed output channels,

  The channels form attributes in assertions.
- an interface assertion is a logical formula with the channel identifiers in I and O as free logical variables denoting streams of the respective types.

Example: Component interface specification



Spec name

A transmission component TMC

Input channel

TMC

in x: T

out y: T

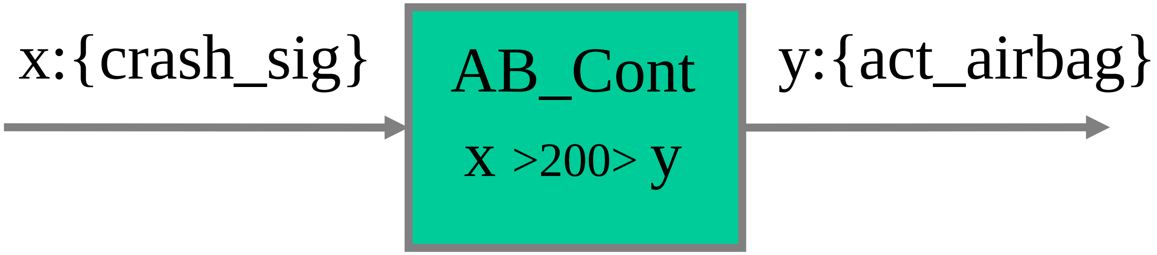
x ~ y

Output channel

$$x \sim y \equiv (\forall\ m \in T: \{m\} © \bar{x} = \{m\} © \bar{y})$$

Interface assertion

Example: Component interface specification – Airbag Controller



An air bag controller

AB_Cont

in x: T

out y: T

x >200> y

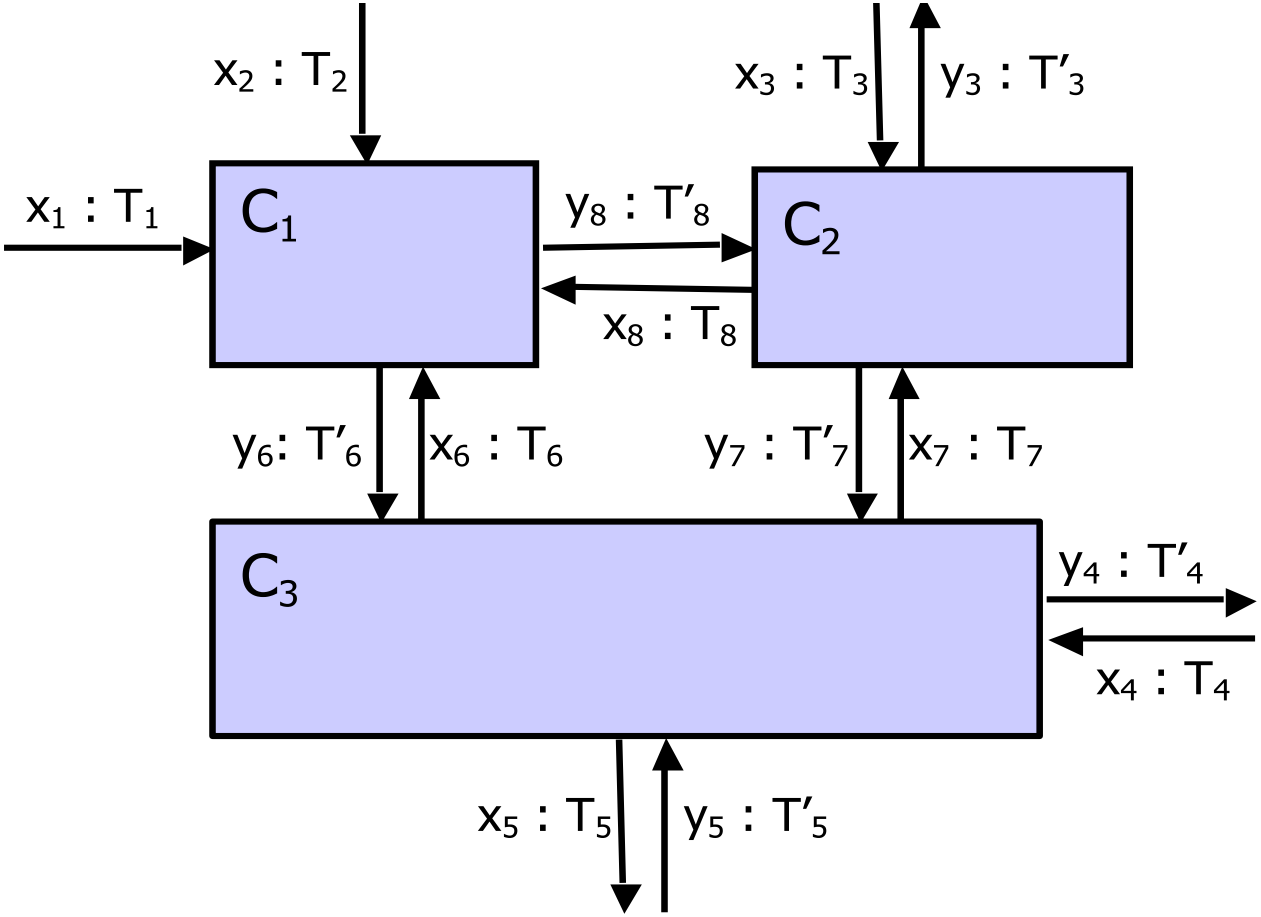
$x >200> y \equiv (\text{"}\ \ t \in \text{Time}:$

$\quad \text{crash\_sig} \in x(t) \Leftrightarrow \text{act\_airbag} \in y(t+200))$

Can we give purely logical specifications of architecture?

Architectures

Specifying Architectures

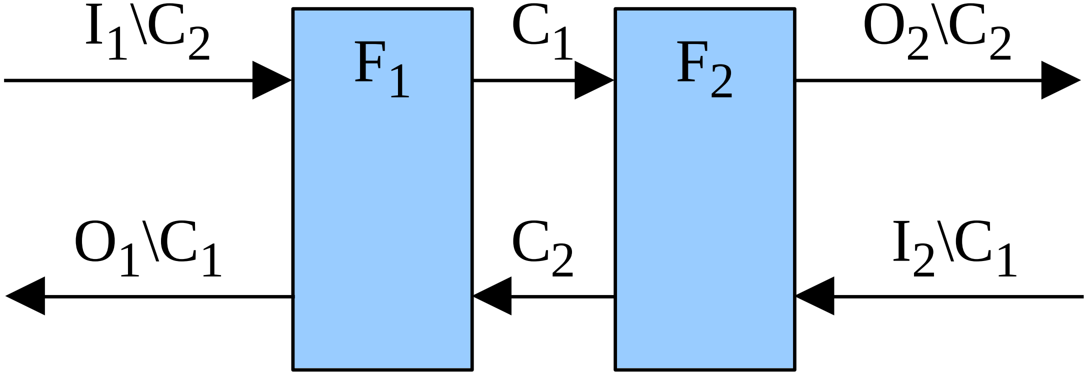


Syntactic Architecture

Composition and Decomposition of Systems

F_1 Î [I_1□ O_1]

F_2 Î [I_2□ O_2]



C_1 = O_1 Ç I_2

C_2 = O_2 Ç I_1

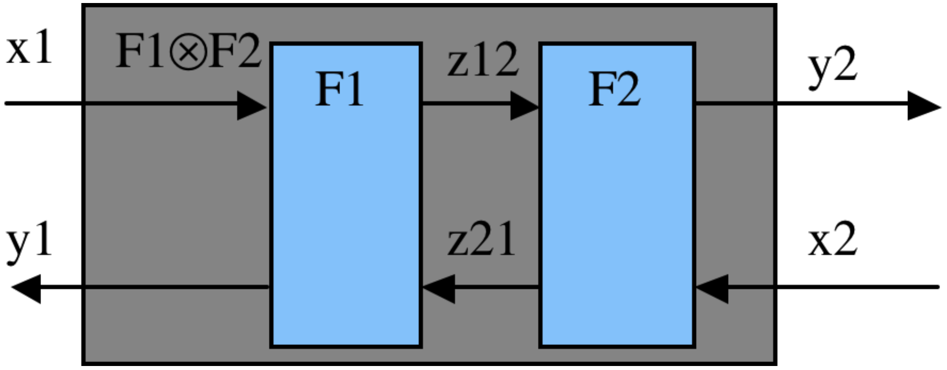
I = $I_1\backslash C_2$ È $I_2\backslash C_1$

O = $O_1\backslash C_1$ È $O_2\backslash C_2$

F_1ÄF_2 Î [I □ O],

(F_1ÄF_2).x = {z|O: x = z|I Ù z|O_1 Î F_1(z|I_1) Ù z|O_2 Î F_2(z|I_2)}

Interface specification composition rule



F1

in x1, z21: T

out y1, z12: T

P1

F2

in x2, z12: T

out y2, z21: T

P2

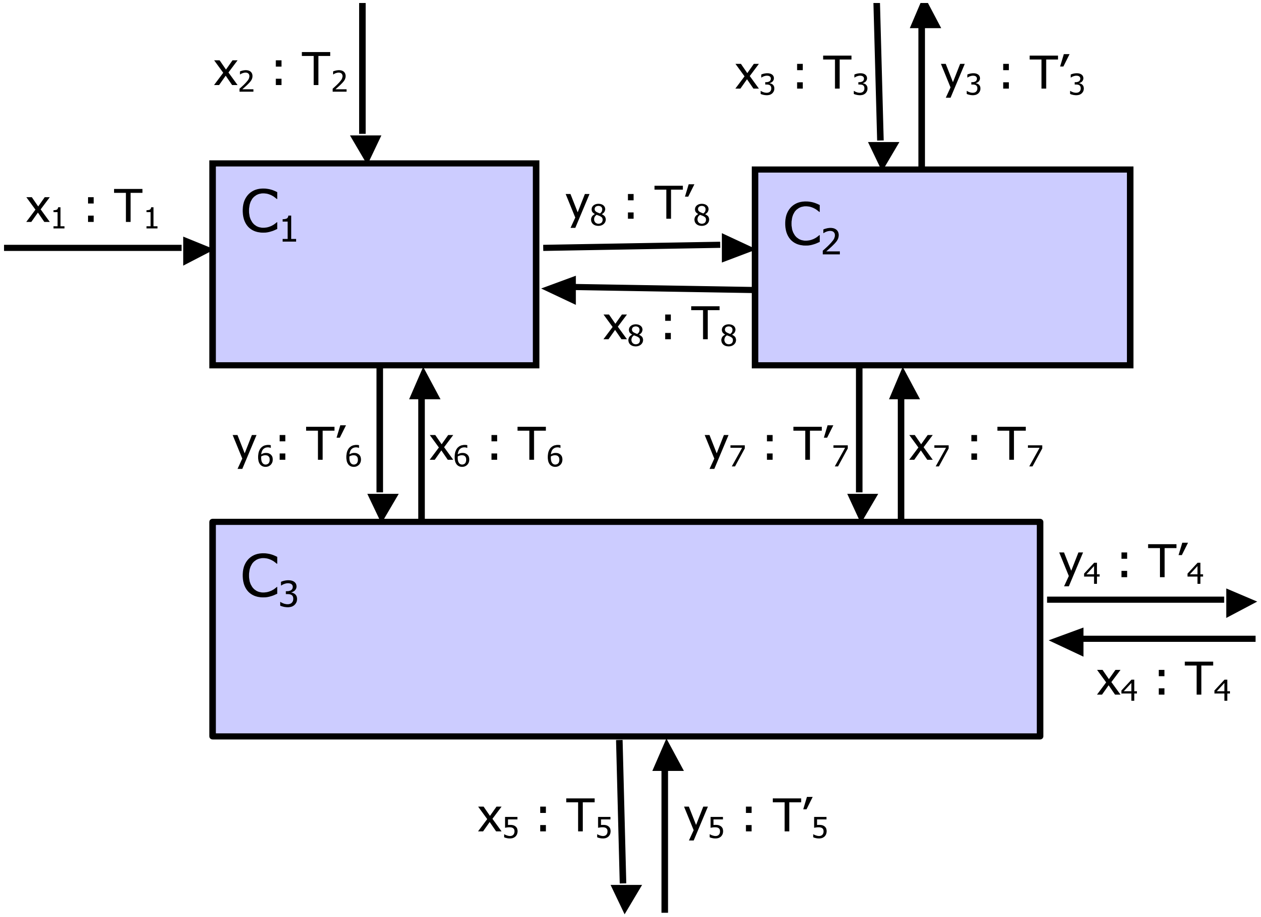
F1⊗F2

in x1, x2: T

out y1, y2: T

∃ z12, z21: P1 ∧ P2

Specifying Architectures



Syntactic Architecture

Specifying Architectures

Set of Composable syntactic Interfaces
A set of component names K with a finite set of interfaces (I_k O_k) for each identifier k Î K is called *composable*, if the following propositions hold:

· sets of input channels I_k, k Î K, are pairwise disjoint,

· sets of output channels O_k, k Î K, are pairwise disjoint,

the channels in {c Î I_k: k Î K } Ç {c Î O_k: k Î K } have consistent channel types in {c Î I_k: k Î K } and {c Î O_k: k Î K }.

Specifying Architectures

Syntactic Architecture

A syntactic architecture $A = (K, x)$ with interface (I_A▯ O_A) is given by a set K of component names with composable syntactic interfaces $x(k)$ = (I_k▯ O_k) for k Î K.

I_A = {c Î I_k: k Î K }\\{c Î O_k: k Î K } set of *input* channels,

D_A = {c Î O_k: k Î K } set of *generated* channels,

O_A = D_A \\ {c Î I_k: k Î K } set of *output* channels,

Z_A = D_A\\O_A set of *internal* channels

C_A = {c Î I_k: k Î K } È {c Î O_k: k Î K set of all channels

By (I_A▯ D_A) we denote the *syntactic internal interface* and by (I_A▯ O_A) we denote the *syntactic external inte*rface of the architecture.

Interpreted and Specified Architecture

Definition. Interpreted Architecture

An interpreted architecture (K, y) for syntactic architecture (K, x) associates an interface behavior $y(k)$ Î $[I_k$ $O_k]$, where $x(k) = (I_k$ $O_k)$, with every component k Î K.

Definition. Specified Architecture

A specified architecture (K, z) for syntactic architecture (K, x) associates an interface assertion $z(k)$ with every syntactic interface $x(k) = (I_k$ $O_k)$ and every component k Î K.

Interface Behavior of Interpreted Architectures: Glass Box View

For an interpreted architecture A

the glass box interface behavior [´] A Î [I_A▯ D_A] is given by (let y (k) = F_k):

([´] A)(x) =

$\{ y \ Î \ \vec{D}_A : \$ z \ Î \ \vec{C}_A : x = z|I_A \ Ù \ y = z|D_A \ Ù \ " \ k \ Î \ K : z|O_k \ Î \ F_k(z|I_k) \}$

where the operator | denotes the usual restriction operator.

Interface Behavior of Interpreted Architectures: black box view

In a black box view Ä A Î [I_A▯ O_A] we hide internal channels

Ä A =

$$\{y\ Î\ \vec{O}_A : \$\ z\ Î\ \vec{C}_A : x = z|I_A\ Ù\ y = z|O_A\ Ù\ "\ k\ Î\ K: z|O_k\ Î\ F_k(z|I_k)\ \}$$

Ä A describes the interface behavior of the architecture.

Specifying Architectures by Assertions

Given composable systems $k \in K$ with specifying interface assertions C_k the specification of the architecture reads

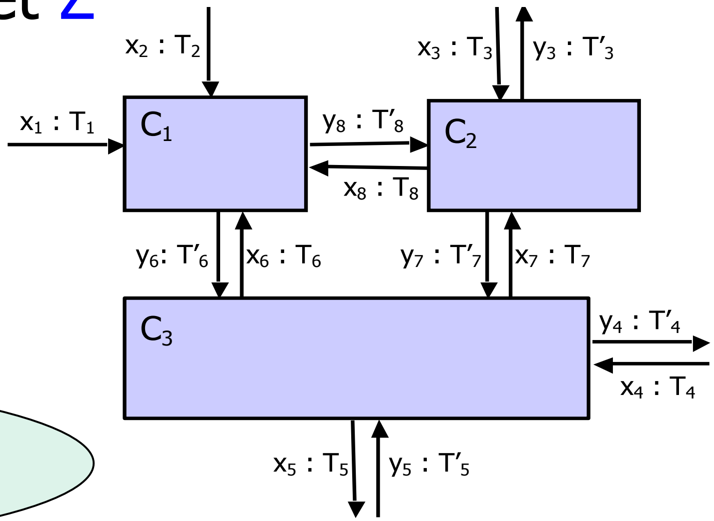
$$\wedge \{C_k: k \in K\}$$

open (glass box)view

and the interface assertion of the composed is given by hiding the internal channels in set Z

$$\exists Z: \wedge \{C_k: k \in K\}$$

cosed (black box) view



Syntactic Architecture

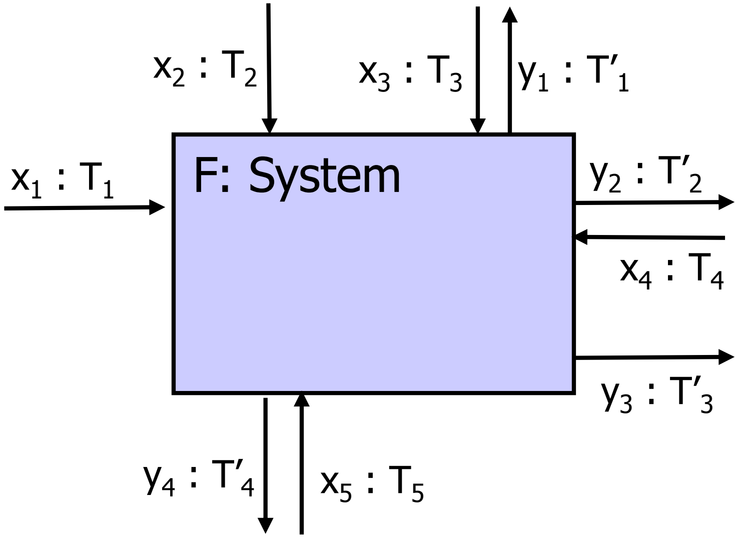
Where are we?

- Representing artifacts by logical concepts - assertions
- Relating assertions by logical concepts
  - ◊ Dependency, Overlap, Inconsistency
  - ◊ Translators for assertions at different levels of abstraction
- Representing systems by assertions
  - ◊ What is a system?
  - ◊ How to define interfaces?
  - ◊ What is an architecture?
  - ◊ How to compose sub-systems by assertions in a modular way?

Representing Artifacts by Assertions: Functional Specification – Feature Specification

How to structure system functionality?

- Typically systems offer a rich functionality structured into functional features
- A functional feature can be represented by some interface behavior [I▸O]
- Interface behavior of functional features can be composed the same way as sub-systems are composed



What is a feature …

- Is a feature just a name … ?
  - ◊ If yes – for what?
  - ◊ What is the relation of a feature tree to system models?
- What are relation between features?
  - ◊ Feature interactions?
  - ◊ Requires?
  - ◊ Excludes?
- Is there a way to model features?
  - ◊ How can we find and identify features of a system?
  - ◊ What is the semantic interpretation of a feature tree?
- Is there a way to interpret relations between features such as feature interactions?

Functional (Behavioral) Features

We concentrate on functional (behavioral) features!

- ◊ These are at the level of system level interface behavior!

- A (functional) feature is a sub-function of a multi-functional system
  - ◊ that serves a certain purpose

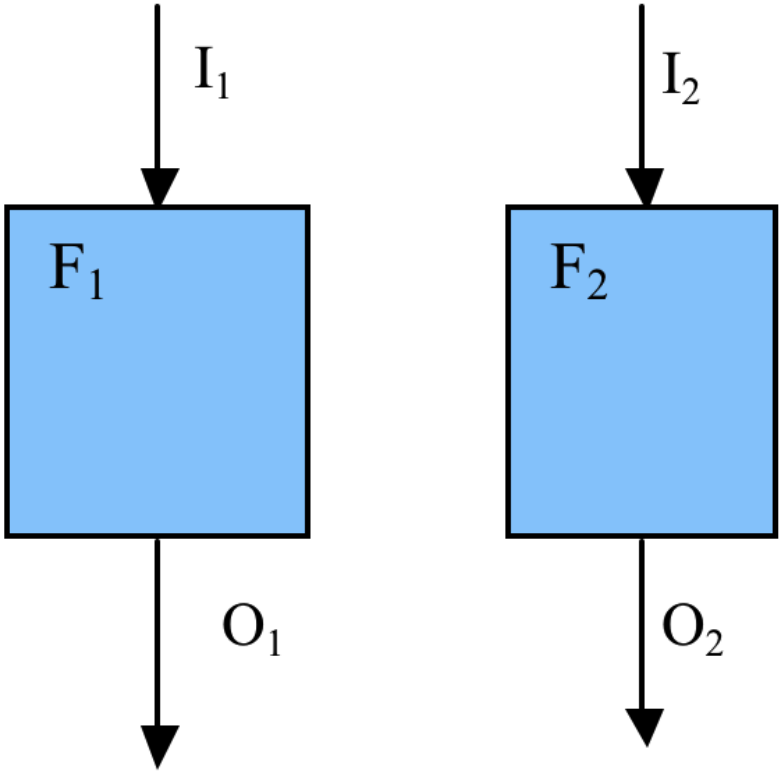
Modeling functional (behavioral) features

- We give a interpretation of the notion of a (functional) feature in terms of the system interface model $F \in [I \blacktriangleright O]$
- The functionality of a system is modeled by its interface behavior
- A (functional) feature is modeled by the
  - projection applied to F to the sub-interface $(I' \blacktriangleright O')$ resulting in a sub-interface behavior $F' \in [I' \blacktriangleright O']$
  - absence of feature interactions is modeled by faithful projections
  - feature interactions are modeled by modes

Feature Specification – Constructive Approach

Combining Functions without Interference

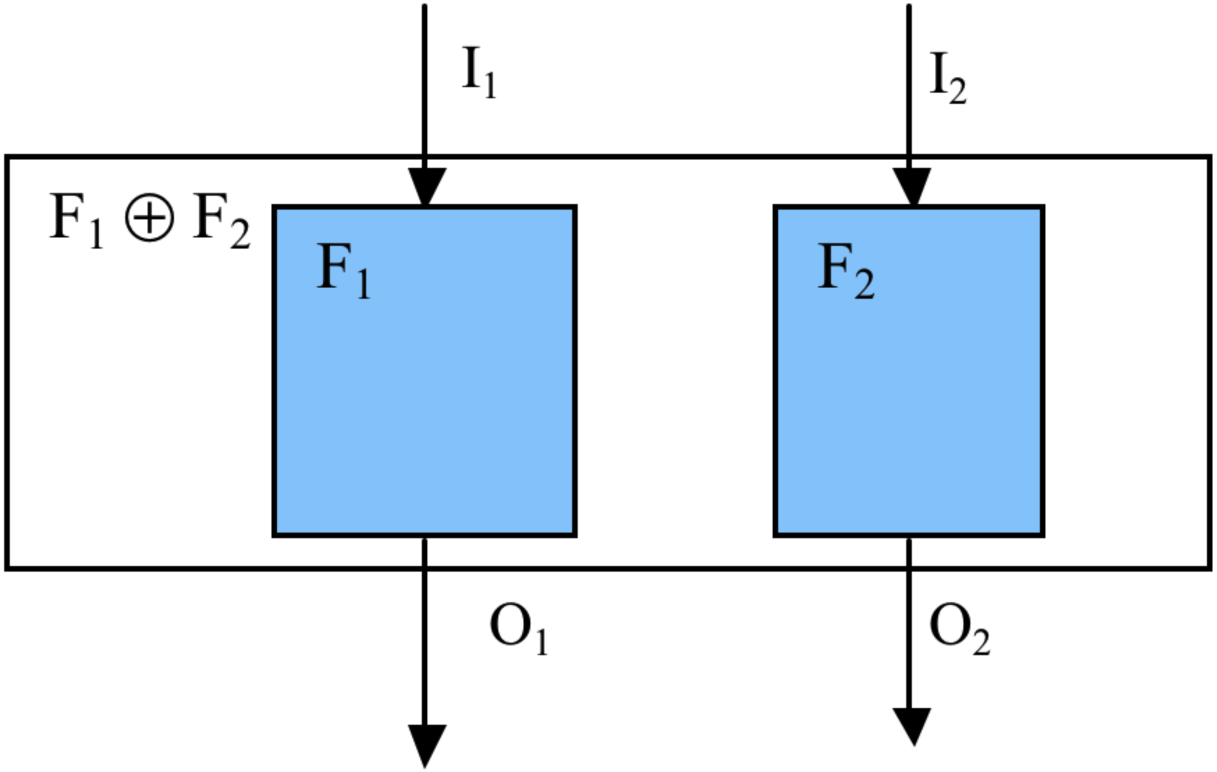
Given two functions F_1 and F_2 in isolation



We want to combine them into a function $F_1 \oplus F_2$

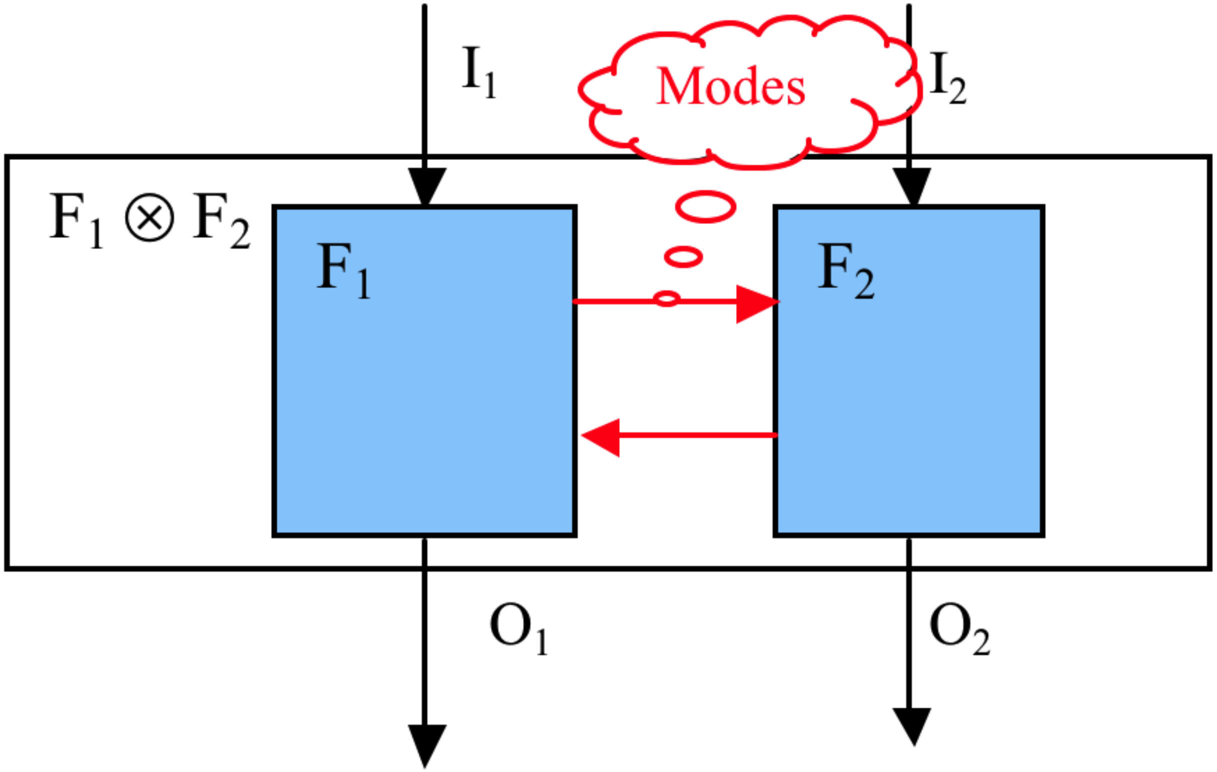
Combining Functions without Interference

Their isolated combination



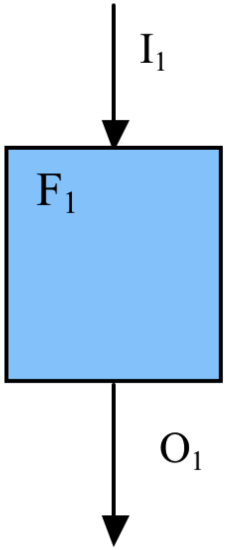
Combining Functions with Feature Interaction

If services F_1 and F_2 have feature interaction we get:

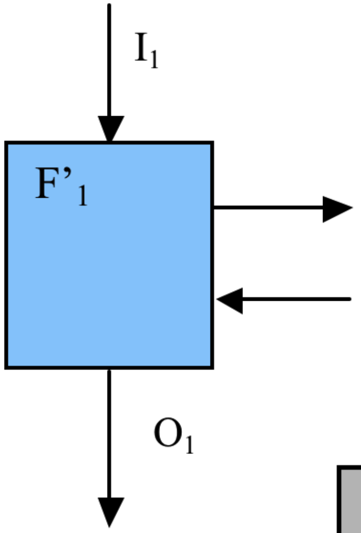


We explain the functional combination $F_1 \otimes F_2$ as a refinement step

The steps of function combination

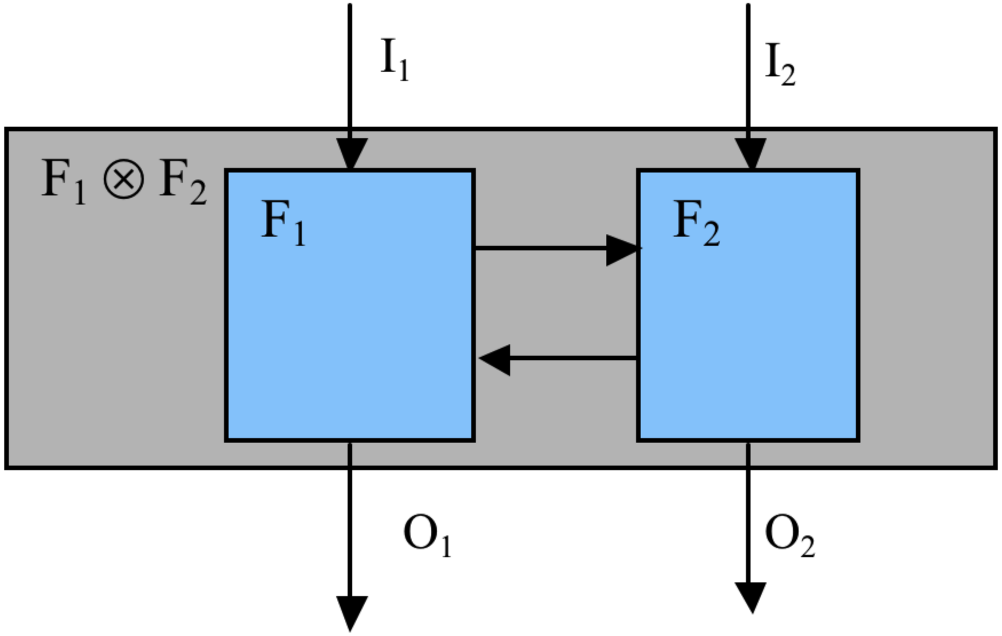


Given the isolated function F_1



We construct a refinement F'_1

And combine F'_1 with a refinement F'_2 of F_2



Feature Specification – Analytic Approach

Functional view: functional decomposition

- The system interface behaviour F as specified by the system requirements specification is structured
  - ◊ into a set H of sub-interfaces for sub-functions F_1, ... , F_h
  - ◊ for which a set M of mode channels is introduced
  - ◊ such that the functions can be specified independently nevertheless capture their feature interactions
  - ◊ each F_i sub-function is described by
    - a syntactic interface (including mode channels) and
    - an interface assertion B_i for each function

Syntactic sub-interfaces

A typed channel set C′ is called a *sub-type* of a typed channel set C if

- C′ is a subset of C
- The message types of the channels in C′ are subsets of the message sets of these channels in C

We write then

C′ subtype C

Then we denote for the channel history x Î $\vec{C}$ by

x|C′ Î $\vec{C}$!

the restriction of x to the channels and messages in C′

Sub-types between interfaces

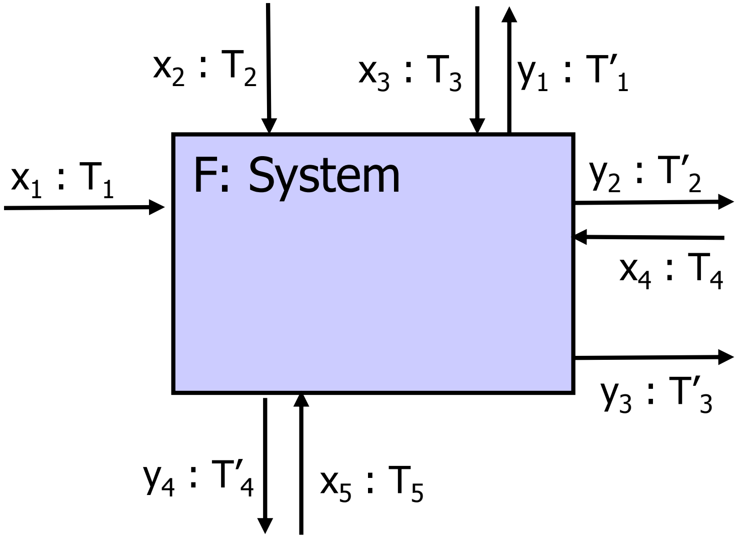
For syntactic interfaces (I ▶ O) and (I′ ▶ O′) where

I′ **subtype** I and O′ **subtype** O

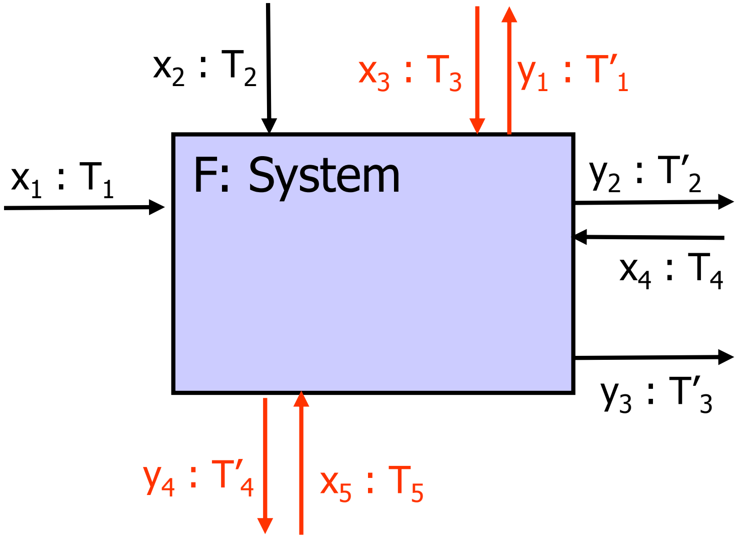
we call (I′□ O′) a sub-type of (I ▶ O) and write:

(I′ ▶ O′) **subtype** (I ▶ O)

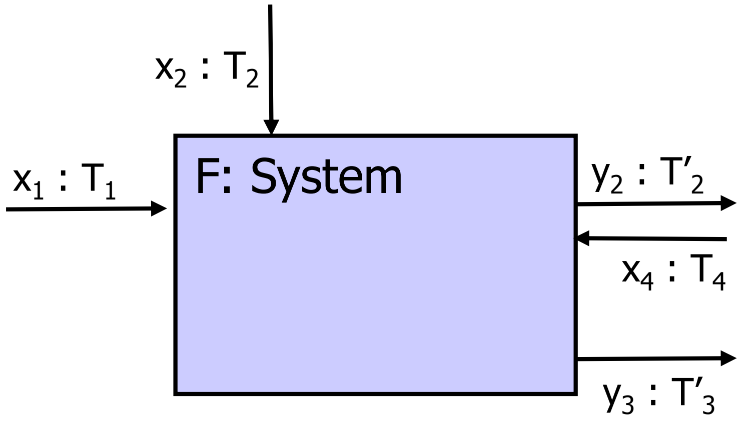
From overall syntactic system interfaces …



to …



sub-interfaces



Projection

Given:

(I′ ▸ O′) **subtype** (I ▸ O)

define for a behavior function F Î [I O] its *projection*

F†(I′ O′) Î [I′ O′]

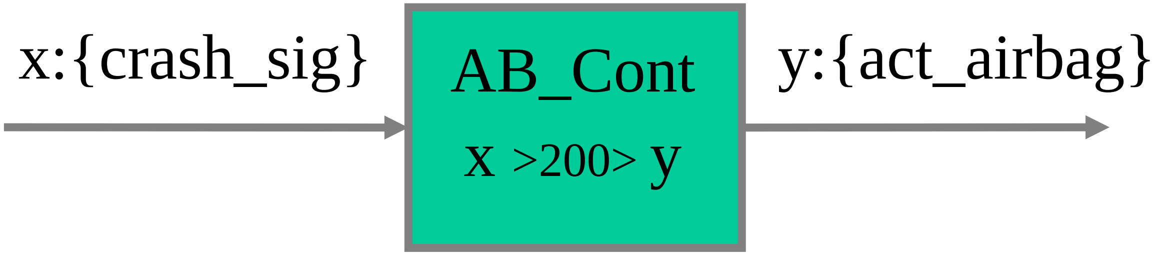
to the syntactic interface (I′ O′) by (for all x′ Î $\vec{I}$′):

F†(I′ O′)(x′) = {y|O′: $ x Î $\vec{I}$: x′ = x|I′ Ù y Î F(x)}

The projection is called *faithful*, if for all x Î dom(F)

F(x)|O′ = (F†(I′ O′))(x|I′)

Example: Component interface specification – Airbag Controller



An air bag controller

AB_Cont

in x: T

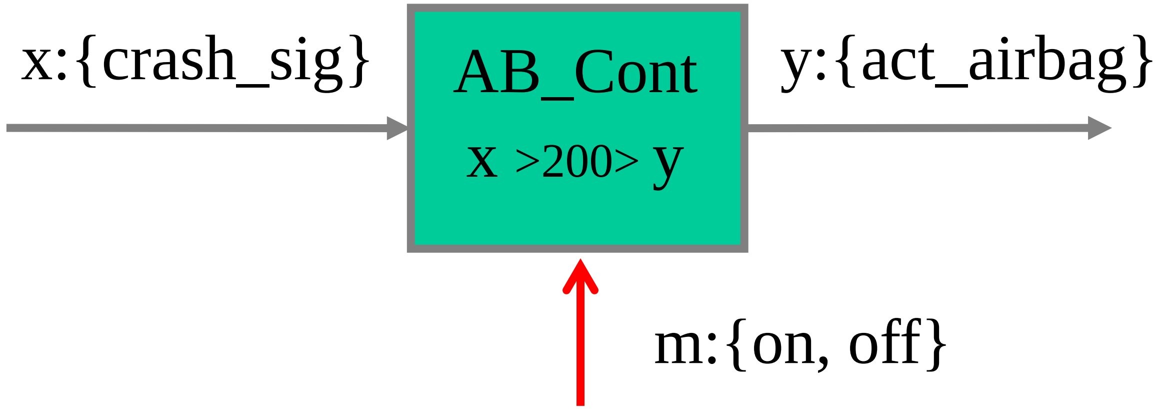
out y: T

x >200> y

$x >200> y \equiv ("\ \ t \in \text{Time}:$

$\quad \text{crash\_sig} \in x(t) \Leftrightarrow \text{act\_airbag} \in y(t+200))$

Example: Component interface specification – Airbag Controller



An air bag controller

AB_Cont

in x: T, m: {on, off}

out y: T

x >200> y

x >200> y ≡ (" t ∈ Time:

(ON(m, t+199) ∧ crash_sig ∈ x(t)) ⇔ act_airbag ∈ y(t+200)

ON(m, t) = if t = 0 then false elif on ∈ m(t) then true
elif off ∈ m(t) then false else ON(m, t-1) fi

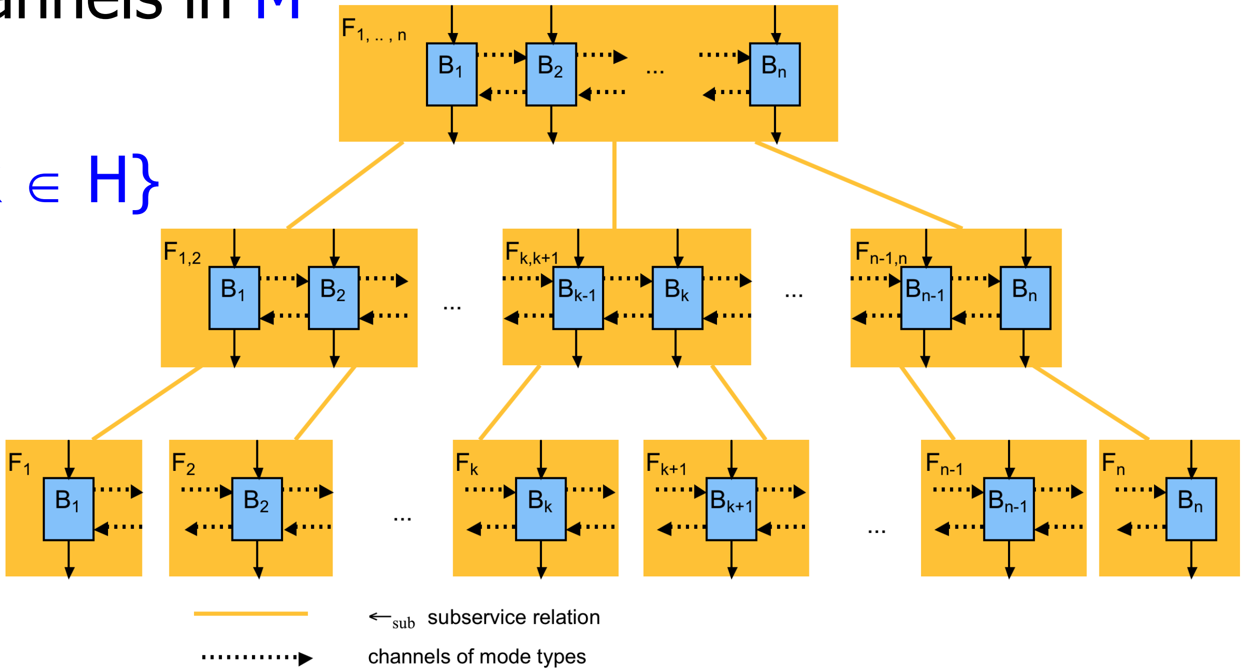
Specifying Architectures by Assertions

Given composable feature interface specifications $h \in H$ with specifying interface assertions B_h the assertion of the functional specification reads

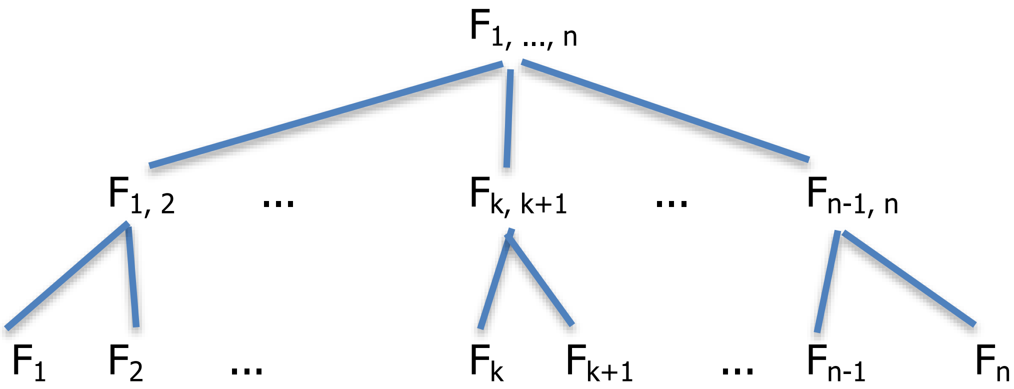
$$\wedge \{B_h : h \in H\}$$

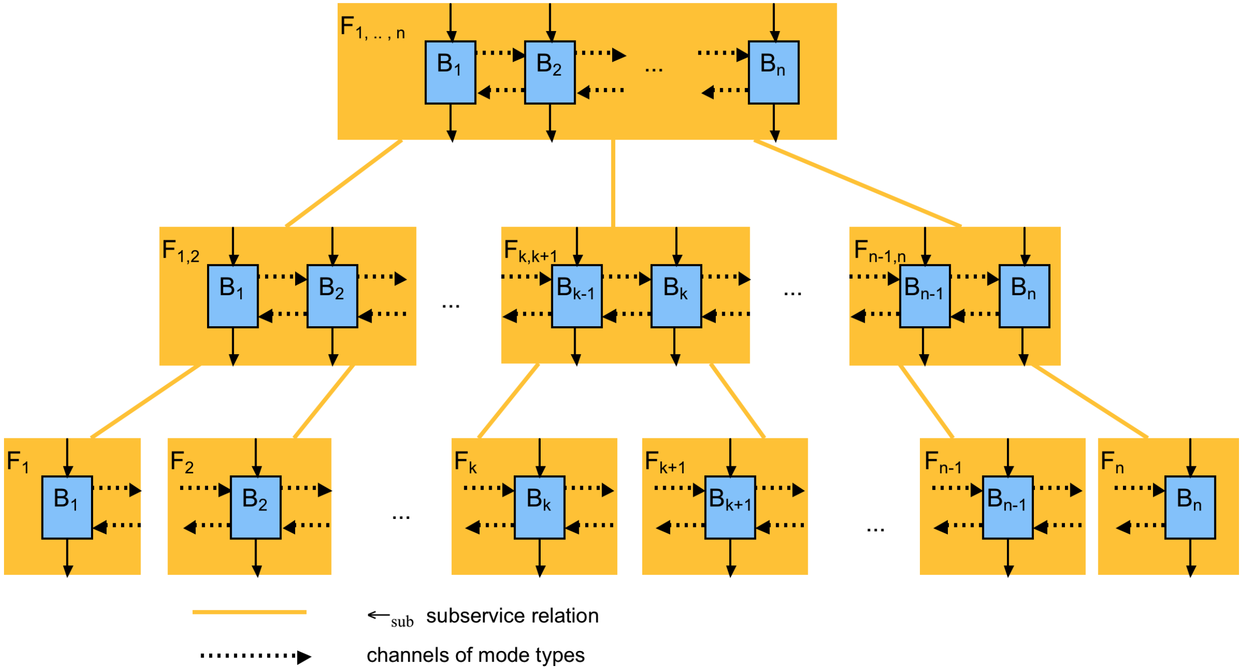
and the interface assertion of the composed is given by hiding the mode channels in M

$$\exists\ M: \wedge \{B_h : k \in H\}$$



An interpreted feature tree





Artifacts: Structure and Content

Artifacts: Structure and Content

- An artifact is a (perhaps virtual) document that
  - ◊ has a structure
  - ◊ provides some content
- This indicates that an artifact presents content in some structured way
- The content has
  - ◊ a syntactic form
  - ◊ a semantics (obtained by the interpretation of the syntactic form)
- Content can be represented
  - ◊ informally (using natural language, diagrams etc.)
  - ◊ formally (using formulas – in our case assertions)
- We call pieces of contents “content chunks”

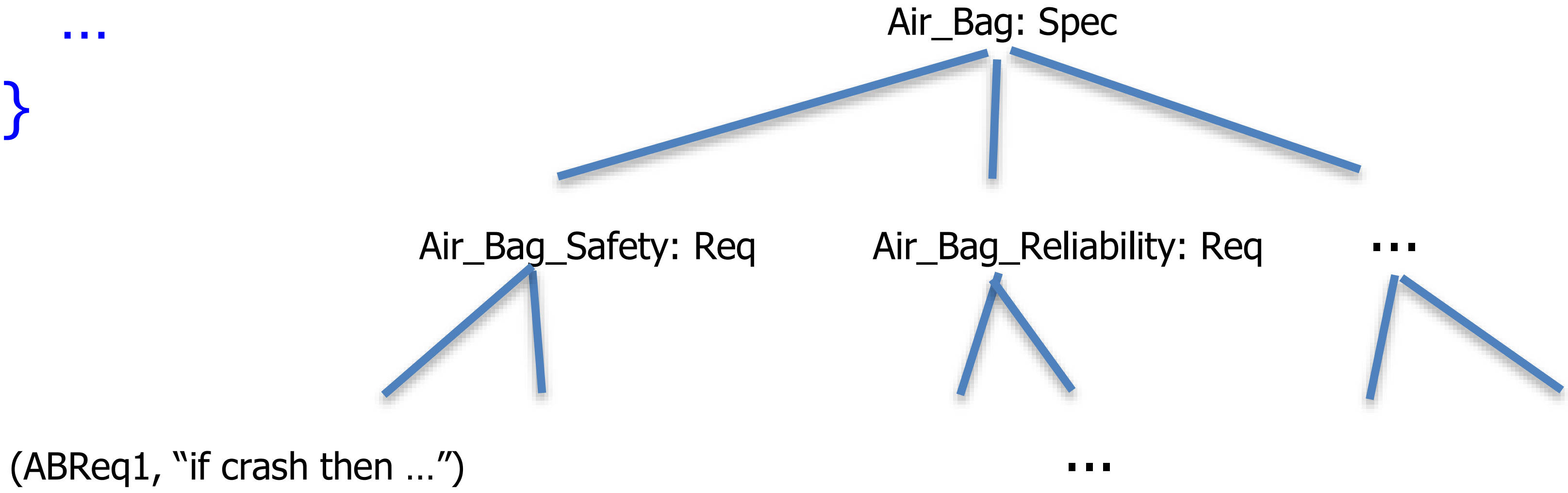
Formally: Named Content Chunks

- An elementary named content chunk is a pair (id, ct) where
  - ◊ id is a unique identifier (which may be typed) and
  - ◊ ct is an elementary content chunk
- A composed named content chunk is a set of
  - ◊ elementary content chunks, or
  - ◊ composed named content chunks

Hierarchies of named content chunks

- A composed named content chunk can represent a hierarchy of named content chunks:

```
(Air_Bag: Spec,
  {(Air_Bag_Safety: Req,   {(ABReq1, “if crash then …”),
                            …},
    (Air_Bag_Reliability: Req: { … },
     …
  }
)
```



Formally: Artifacts

- An artifact is a hierarchy of named content chunks

Artifacts and their Named Content Chunks

- Given an artifact $E = (id, ct)$ its set $NCoCh(E)$ of named content chunks is:

  $NCoCh((id, ct)) = \{(id, ct)\}$

  if ct is an elementary content chunk

  $NCoCh((id, ct)) = \{(id, ct)\} \cup (\cup\{NCoCh(t): t \in ct\})$

  if ct is a set of named content chunks

- $NCoCh(E)$ denotes the set of named content chunks – that are unique since the identifiers are unique
  - ◊ allows forming finite hierarchies of named content chunks by nested sets of properties.
  - ◊ By construction, each content chunk in the hierarchy has a name and which each name content is associated.

Artifacts and their Content Chunks

- Given artifact $E = (id, ct)$ we define its set

  $Co(NCoCh(E))$

  of content chunks as follows:

  $Co(\{(id, ct)\}) = \{ct\}$

  if ct is an elementary content chunk

  $Co(\{(id, ct)\}) = \cup\{Co(NCoCh(t)): t \in ct\})$

  if ct is a set of named content chunks

  $Co(S1 \cup S2) = Co(S1) \cup Co(S2)$

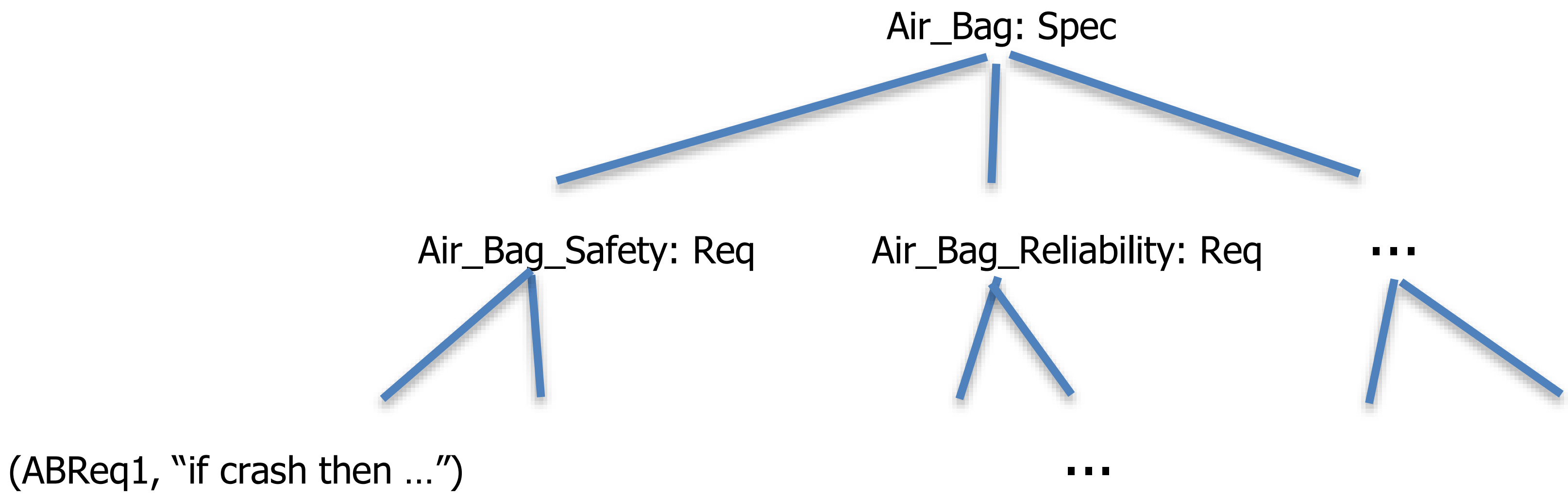
  if $S1$ and $S2$ are nonempty sets
- If the content chunks are assertions, then the meaning of the artifacts is given by

  $\wedge\ Co(CoCh(E))$

Artifacts as named hierarchies of content

With these concepts

- An artifact (id, ct) is structured into a hierarchy of named content chunks
- NCoCh((id, ct)) yields the set of all named content chunks
- Co(NCoCh((id, ct))) yields the set of all elementary (unnamed) contents of artifact (id, ct)



Traceability in Software and System Development

Linking, Tracing, and Relating Artifacts

- A (bilateral) link t defines a directed relation between two named content chunks

  e and e′

  of artifacts E and E′.

  $$(e, e') \in \text{NCoCh}(E) \times \text{NCoCh}(E')$$

  ◊ e is called the source of t and

  ◊ e′ is called the target of t

- We write

  $$\text{src}(t) = e \text{ and } \text{trg}(t) = e'$$

Linking, Tracing: Relating Artifacts and their Content Chunks

- A trace is a nonempty finite sequence of links

  $t_0, t_1, t_2, \ldots, t_n$

  where the source of t_{i+1} is the target of t_i:

  $\mathrm{trg}(t_i) = \mathrm{src}(t_{i+1})$ for $i = 0, 1, \ldots, n-1$

We distinguish between links and traces that

- relate the content chunks of one artifact, called *intra-artifact links*, and links that
- relate the content chunks e of one artifact E to those of a different artifact E′, called *inter-artifact links*.

Illustration: Tracing

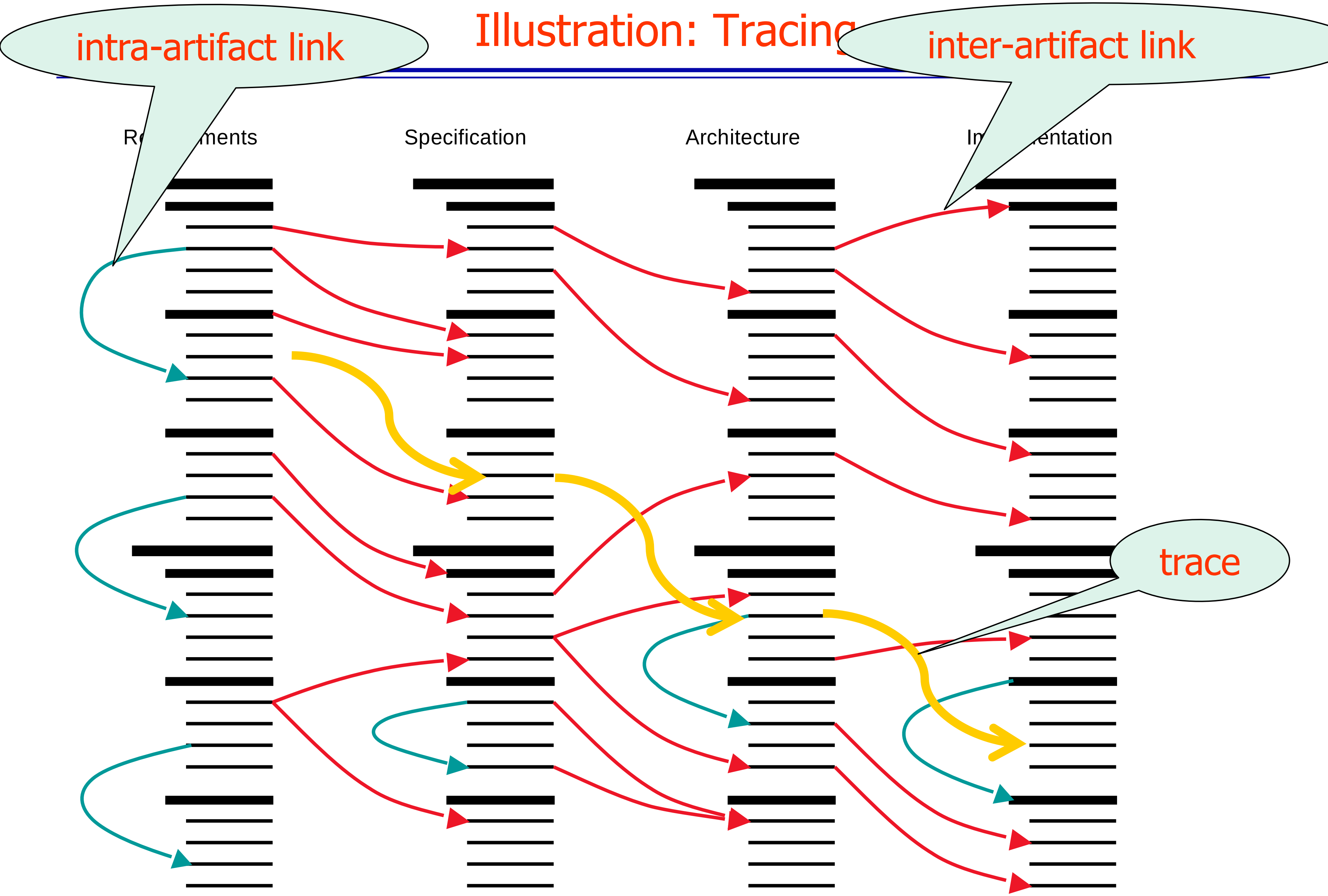


Illustration: Forward Tracing

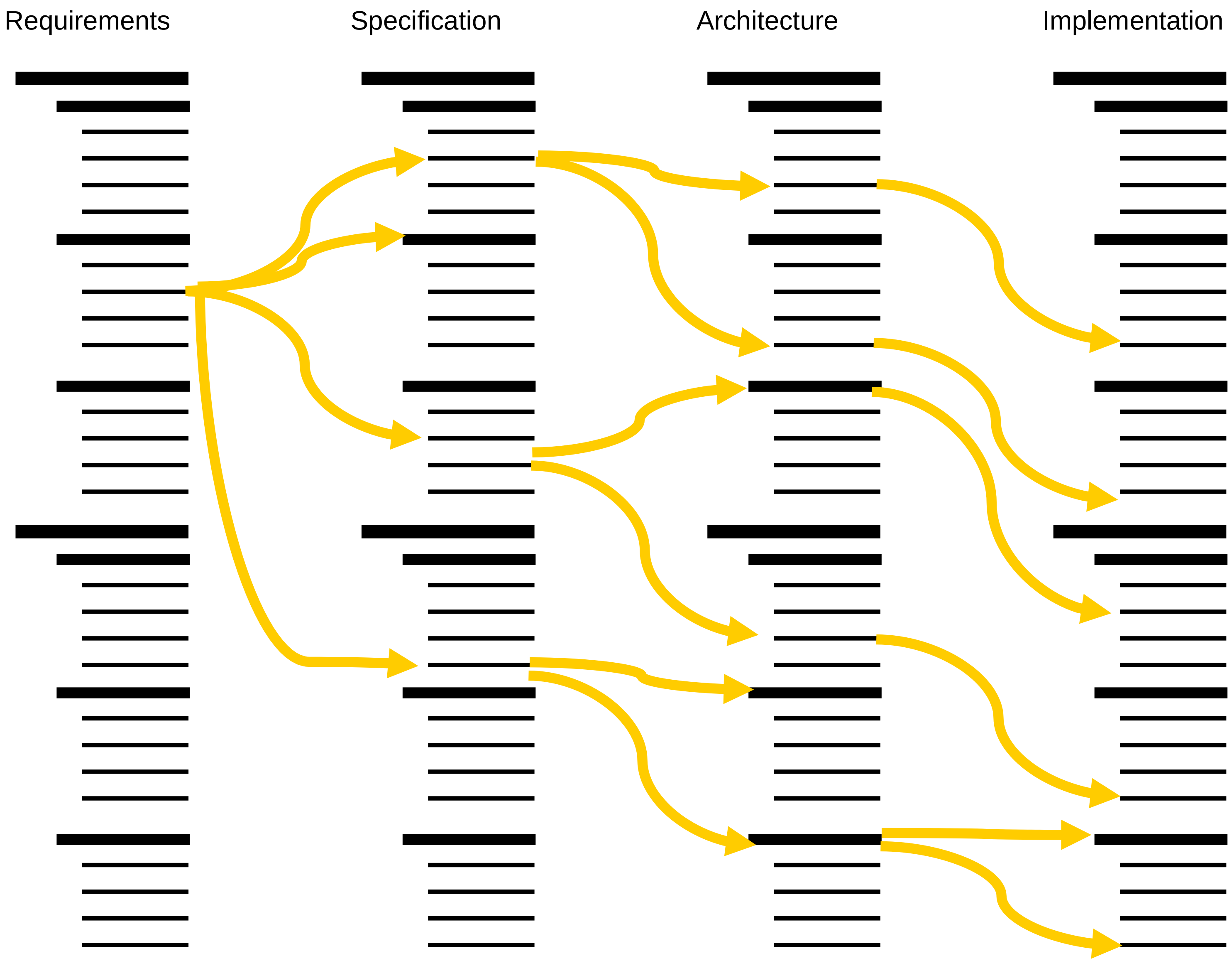
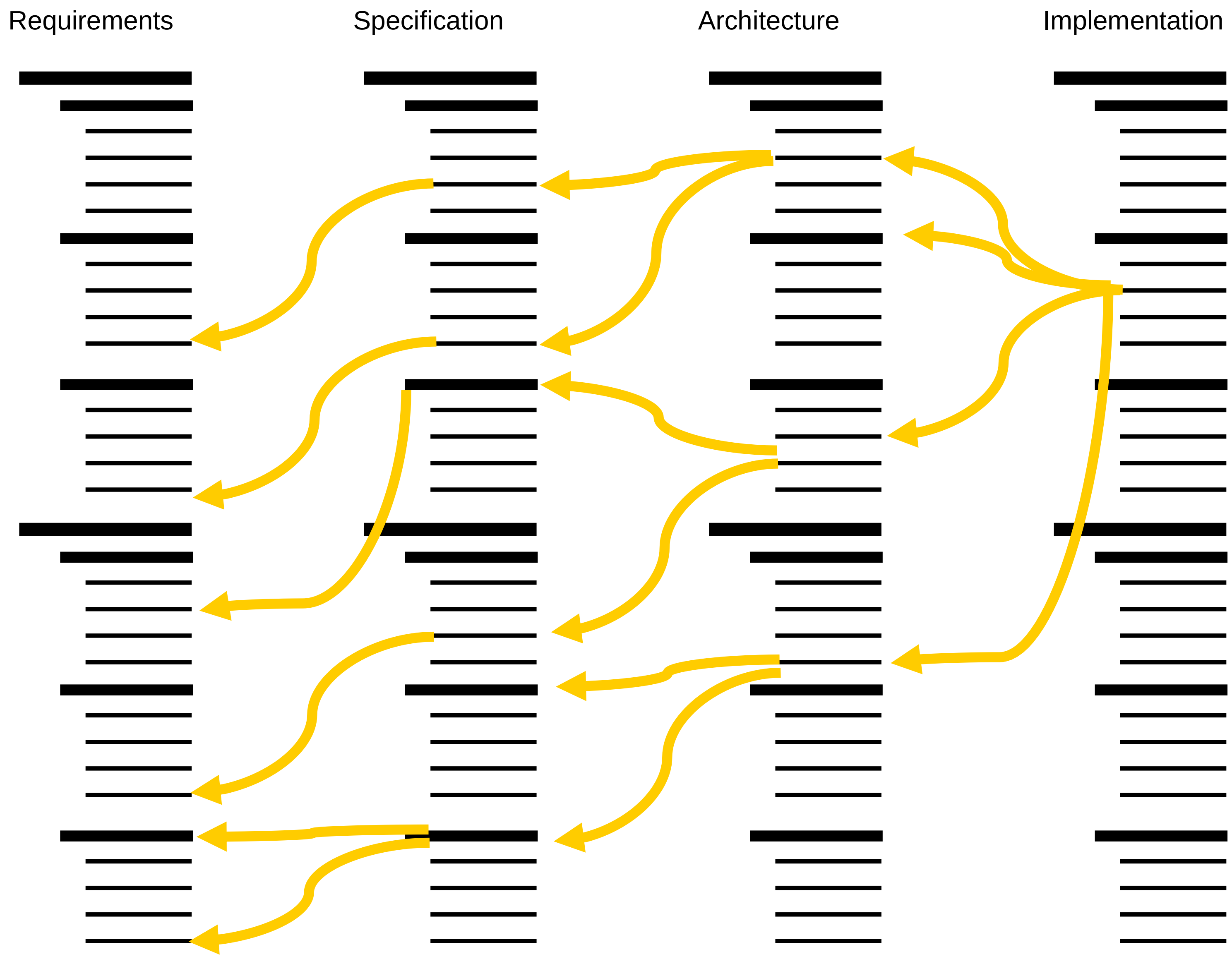


Illustration: Backward Tracing



Meaning of Links and Traces

A link relates two syntactic named content chunks

- A link has a meaning that usually is related to the meaning of the content chunks it relates.
- A link states a proposition about the relationship between its source and its target.
- A link can be valid or invalid.
  - ◊ It is called *valid*, if the proposition associated with the link is true.
  - ◊ Otherwise it is called *invalid*.

Syntax and Meaning of Links

- Syntactically a link is
  - ◊ a relationship between named content chunks of artifacts.
- Semantically a link expresses that
  - ◊ there is a particular property valid for the involved content chunks.

Example: link t with

trg(t) = “Product_Manager: Stakeholder”

src(t) = “High_Usability: Quality_Attribute”.

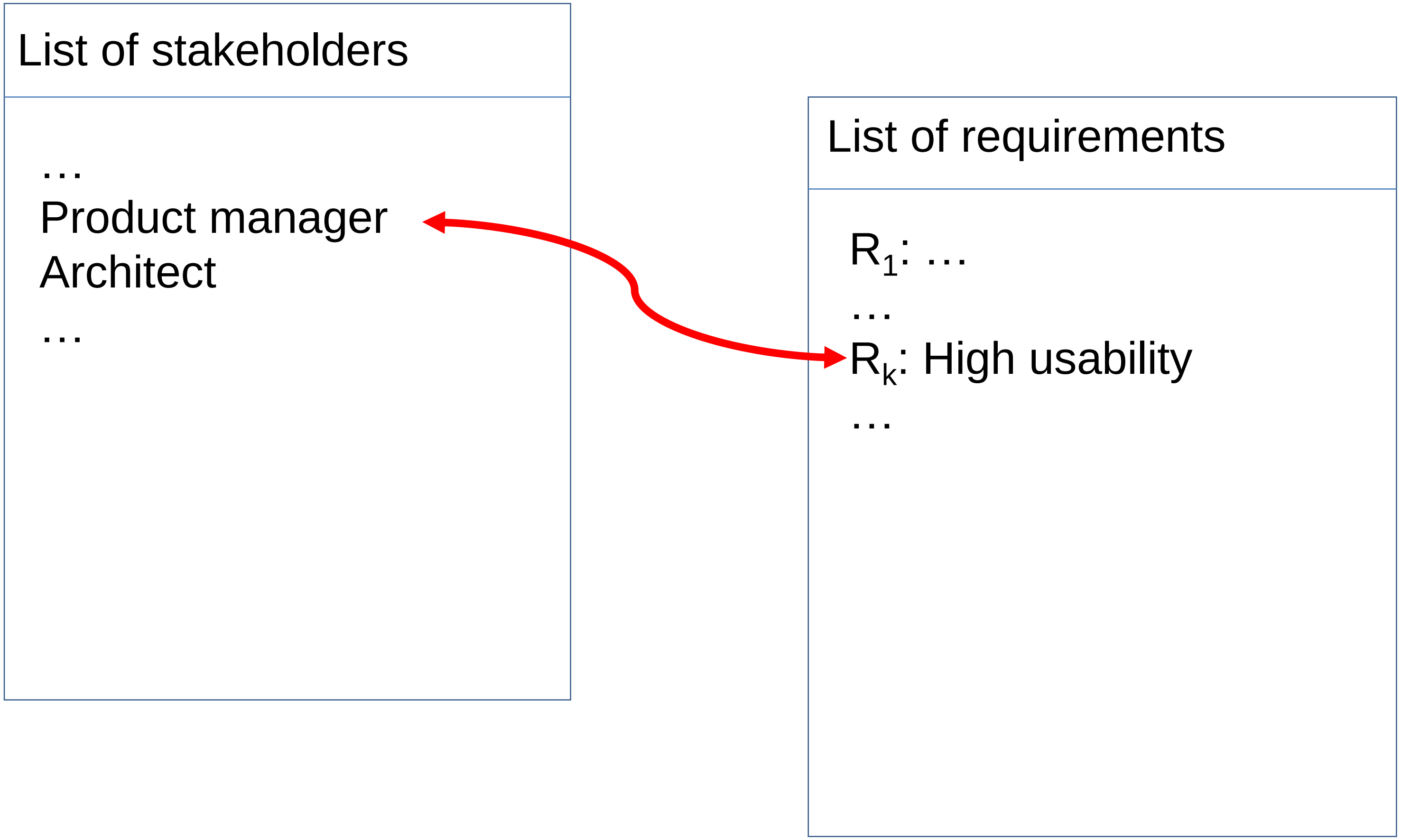
- Link is to express that the stakeholder Product_Manager is the source of the quality requirement High_Usability.
- In other terms, the link has the meaning
  - ◊ (Product_Manager: Stakeholder, High_Usability: Quality_Attribute) $\in$ Source_of_Requirement
  - ◊ where Source_of_Requirement is a relation between stakeholders and requirements.

Formalizing Links and Tracing

We distinguish the following concepts of links

- *supplemental* links*:* link t relating a and z documents relationships between content chunks a and z providing additional information not explicitly contained in artifacts E_k and $E_{k'}$;
  - ◊ Example: link between a stakeholder a and a requirement z that originates from that stakeholder.
- *derived* links*:* link t relating a and z documents relationships between chunks a and z that can be derived from its logical meaning and justified logically (or even proved) from the assertions in artifacts E_k and $E_{k'}$;
  - ◊ Example: specification of a functional property by assertion a and its implementation or refinement by assertion z such that $z \Rightarrow a$.

Example: *supplemental* Link



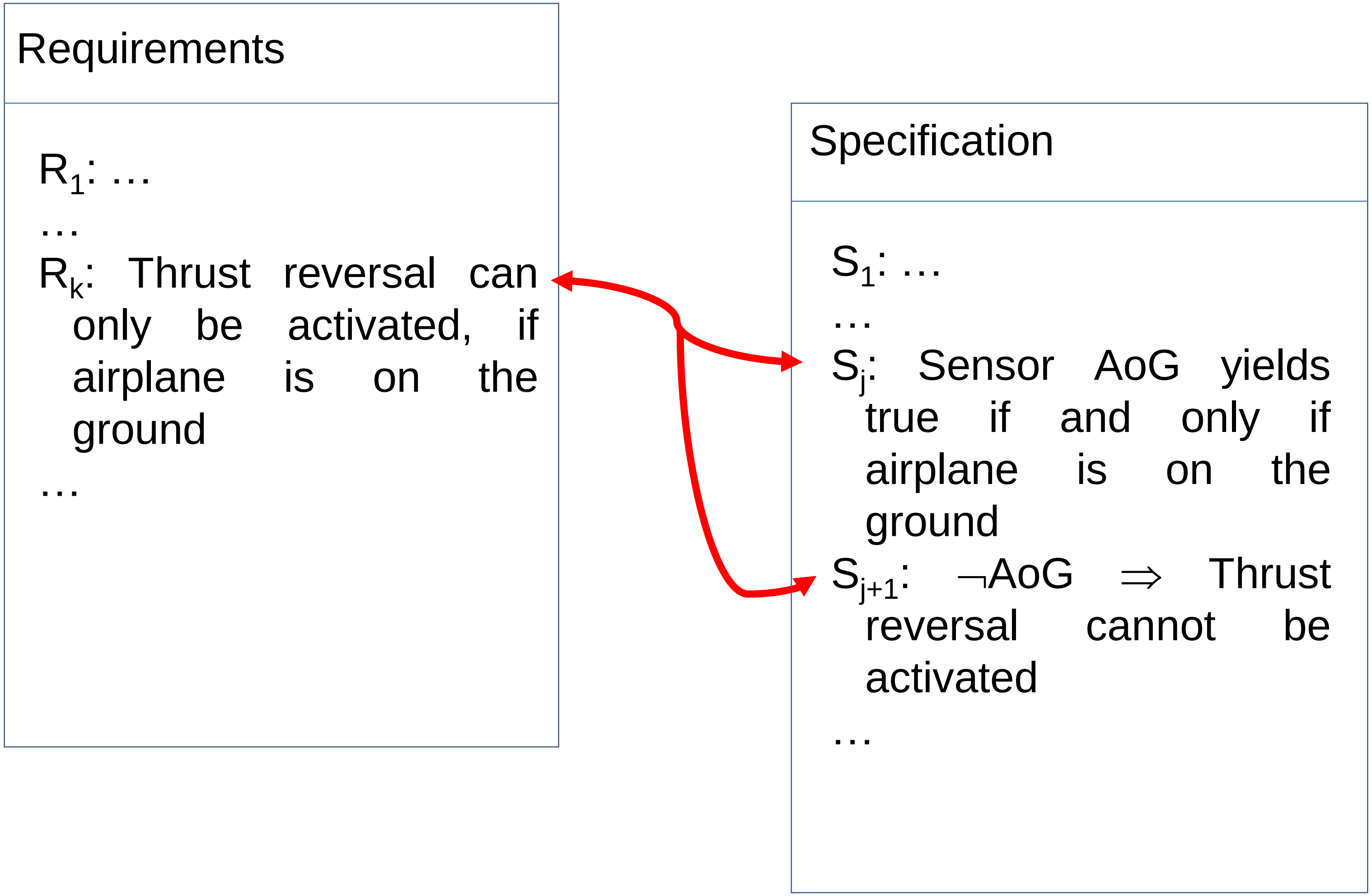
List of stakeholders

…
Product manager
Architect
…

List of requirements

R_1: …
…
R_k: High usability
…

Example: derived Link



Requirements

R_1: …

…

R_k: Thrust reversal can only be activated, if airplane is on the ground

…

Specification

S_1: …

…

S_j: Sensor AoG yields true if and only if airplane is on the ground

S_{j+1}: $\neg$AoG $\Rightarrow$ Thrust reversal cannot be activated

…

Multilateral Links

- A multilateral link t is a directed relation between two named sets of content chunks

$$e \text{ and } e'$$

of artifacts E and E':

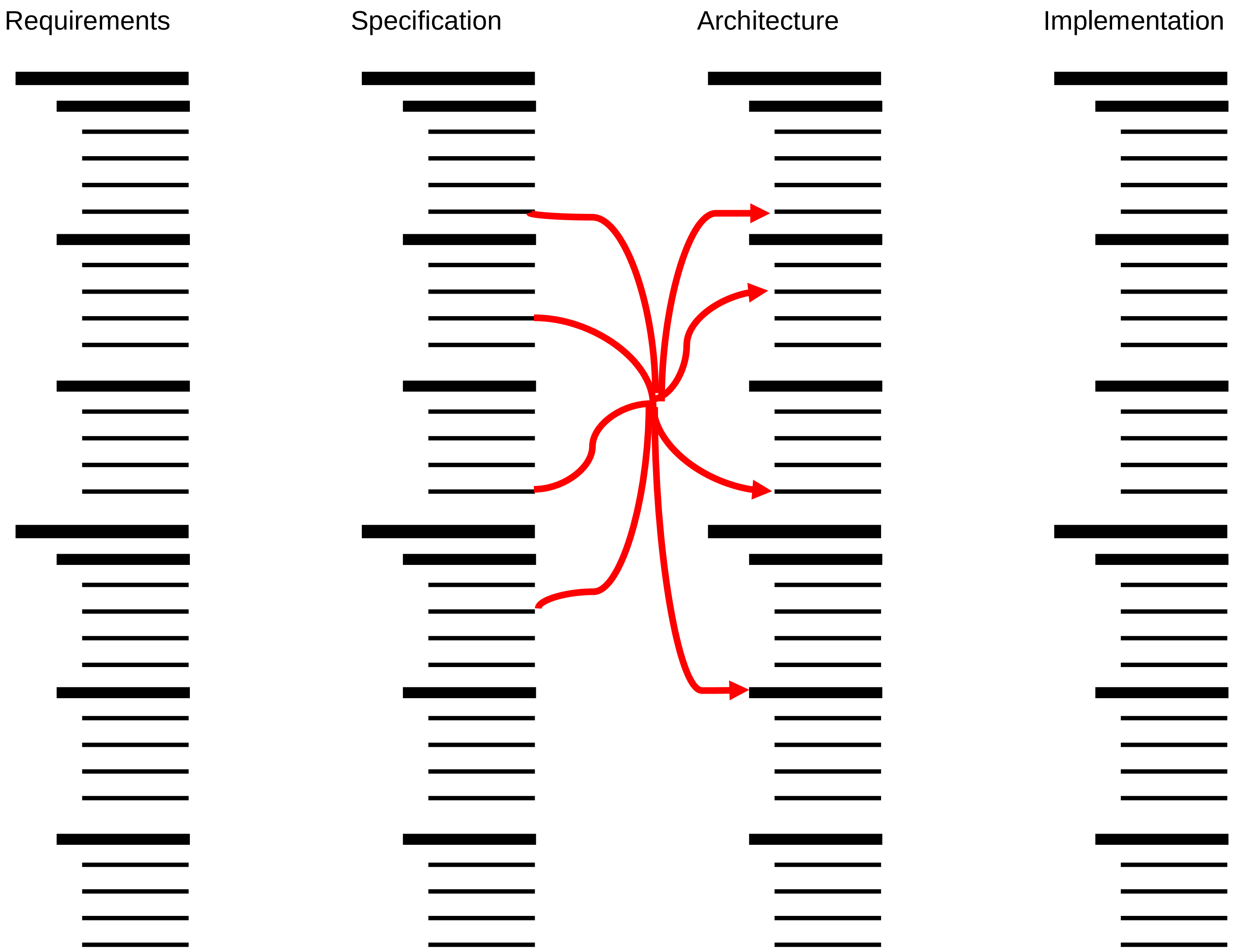
$$(e, e') \in \wp(\mathrm{NCoCh}(E_k)) \times \wp(\mathrm{NCoCh}(E_{k'}))$$

  - ◊ $e \subseteq \mathrm{NCoCh}(E_k)$ is called the source of t and
  - ◊ $e' \subseteq \mathrm{NCoCh}(E_k)$ is called the target of t

- We write

$$\mathrm{src}(t) = e \text{ and } \mathrm{trg}(t) = e'$$

Illustration: Multilateral Tracing



Content of Multilateral Links

- Given multilateral link t relating between content chunks e and e′ of artifacts E and E′:

$$(e, e') \in \wp(\text{NCoCh}(E_k)) \times \wp(\text{NCoCh}(E_{k'}))$$

in case the contents Co(e) and Co(e') are assertions the link relates two sets of of assertions.

Representing Artifacts by Logic: System Requirements

System level functional requirements

- The system interface behaviour F is specified by the system requirements specification

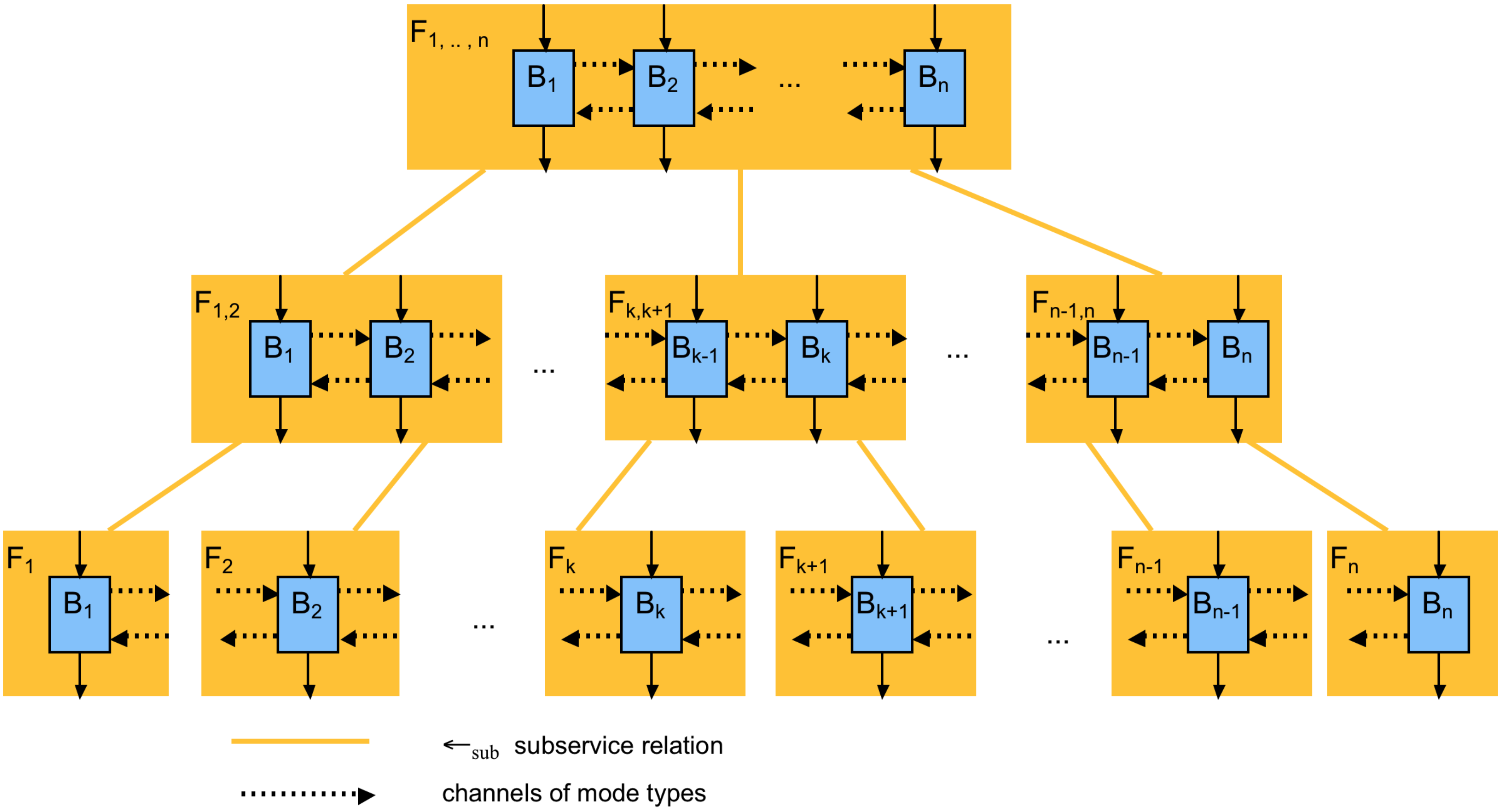
$$A = \{A_i : 1 \leq i \leq n\}$$

where the A_i are interface assertions

	Functiona	Safety	Priority	Component	Function
A_1	...	Yes	high		
A_2	...	No	medium		
A_n	...	no	low		

Representing Artifacts by Logic: Functional Specification

Function / Feature Hierarchy



Functional view: functional decomposition

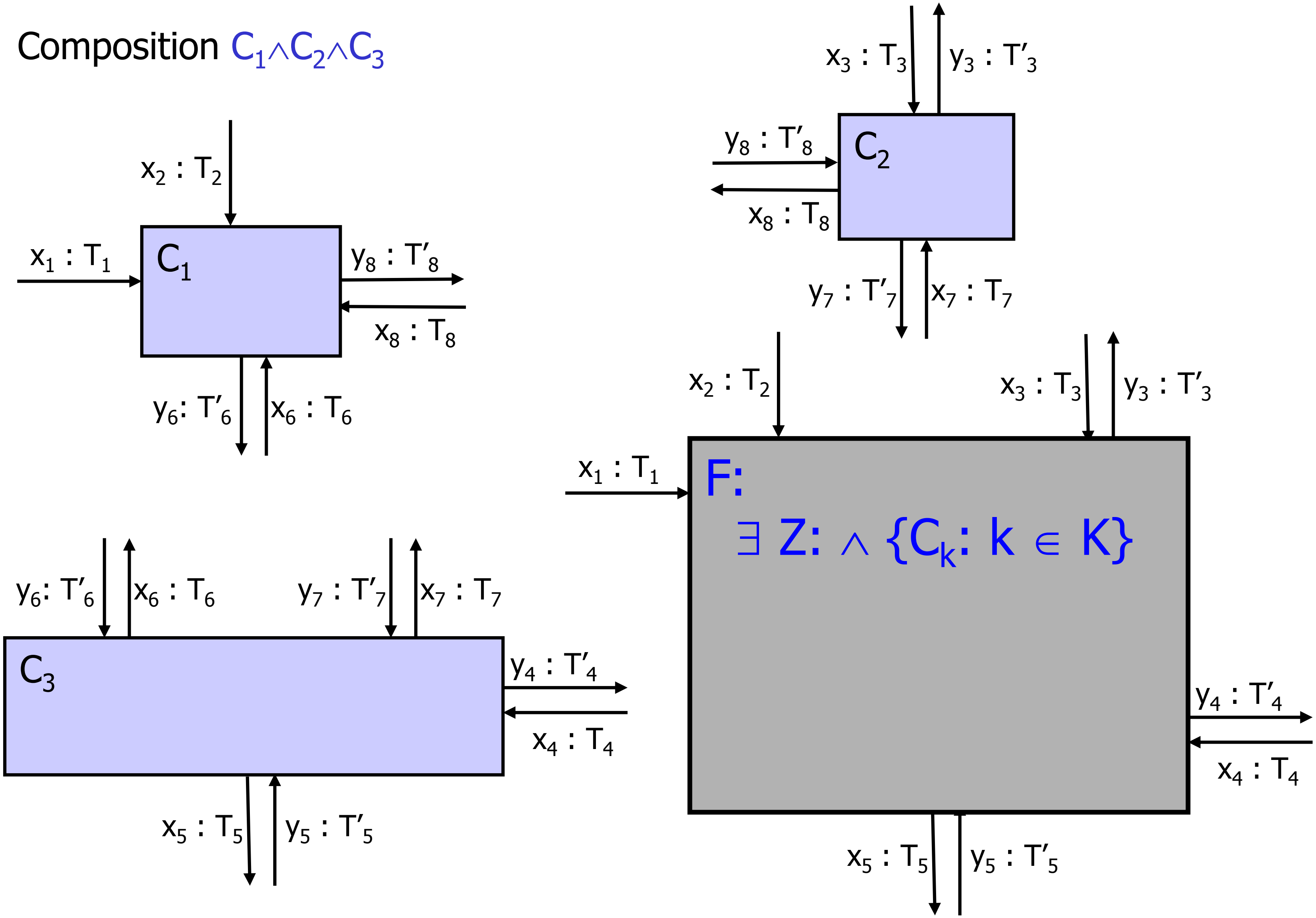
- The system interface behaviour F as specified by the system requirements specification $A = \{A_i: 1 \le i \le n\}$ is structured
  - ◊ into a set of sub-interfaces for sub-functions $F_1, \ldots, F_k$
  - ◊ that are specified independently by introducing a set M of mode channels to capture feature interactions
  - ◊ each F_i sub-function is described by
    - a syntactic interface and
    - an interface assertion B_i such that

$$\wedge \{B_i: 1 \le i \le k\} \Rightarrow A$$

Representing Artifacts by Logic: Architecture

Architecture

- Composition $C_1 \wedge C_2 \wedge C_3$



Specifying Architectures by Assertions

Given composable systems $k \in K$ with specifying interface assertions C_k the specification of the architecture reads

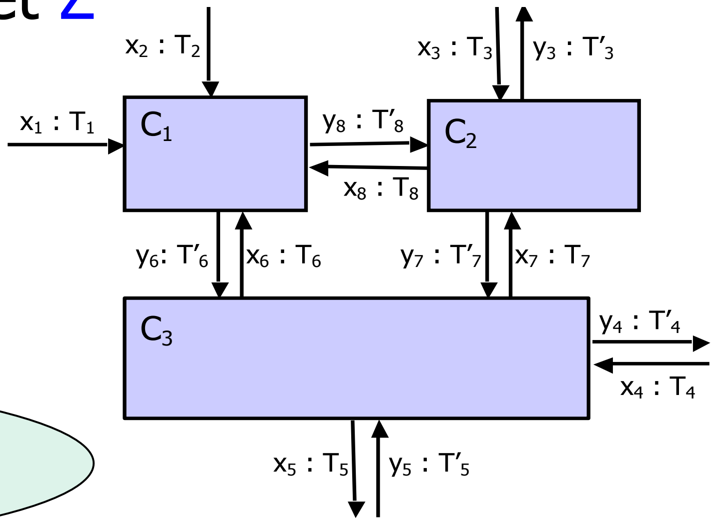
$$\wedge \{C_k : k \in K\}$$

open (glass box)view

and the interface assertion of the composed is given by hiding the internal channels in set Z

$$\exists Z : \wedge \{C_k : k \in K\}$$

closed (black box) view



Syntactic Architecture

Three Artifacts

Three levels of Specification

- Requirements - system level
  - ◊ List of requirements - functional system property
  - ◊ Example: "The activation of safety relevant functions by the pilot is always double checked for plausibility by the system ."
- Functional specification - system level
  - ◊ decomposition of system functionality in hierarchy of (sub-)functions
  - ◊ Specification of (sub-)functions
  - ◊ Specification of dependencies (feature interactions) between (sub-) functions based on a mode concept
  - ◊ Example: "Thrust reversal may only be activated, if the plane is on the ground."
- Architecture specification - component level
  - ◊ decomposition a systems in sub-systems (component)
  - ◊ relationship to data flow diagram
  - ◊ interface specification of component
  - ◊ Example: "The weight sensor indicates that the plane is on the ground."

Three levels of system description in logic

- system level requirements

$$A = \wedge \{A_i : 1 \leq i \leq r\}$$

- functional specification at system level - functionality

$$B = \wedge \{B_i : 1 \leq i \leq n\}$$

- architecture specification

$$C = \wedge \{C_k : 1 \leq k \leq m\}$$

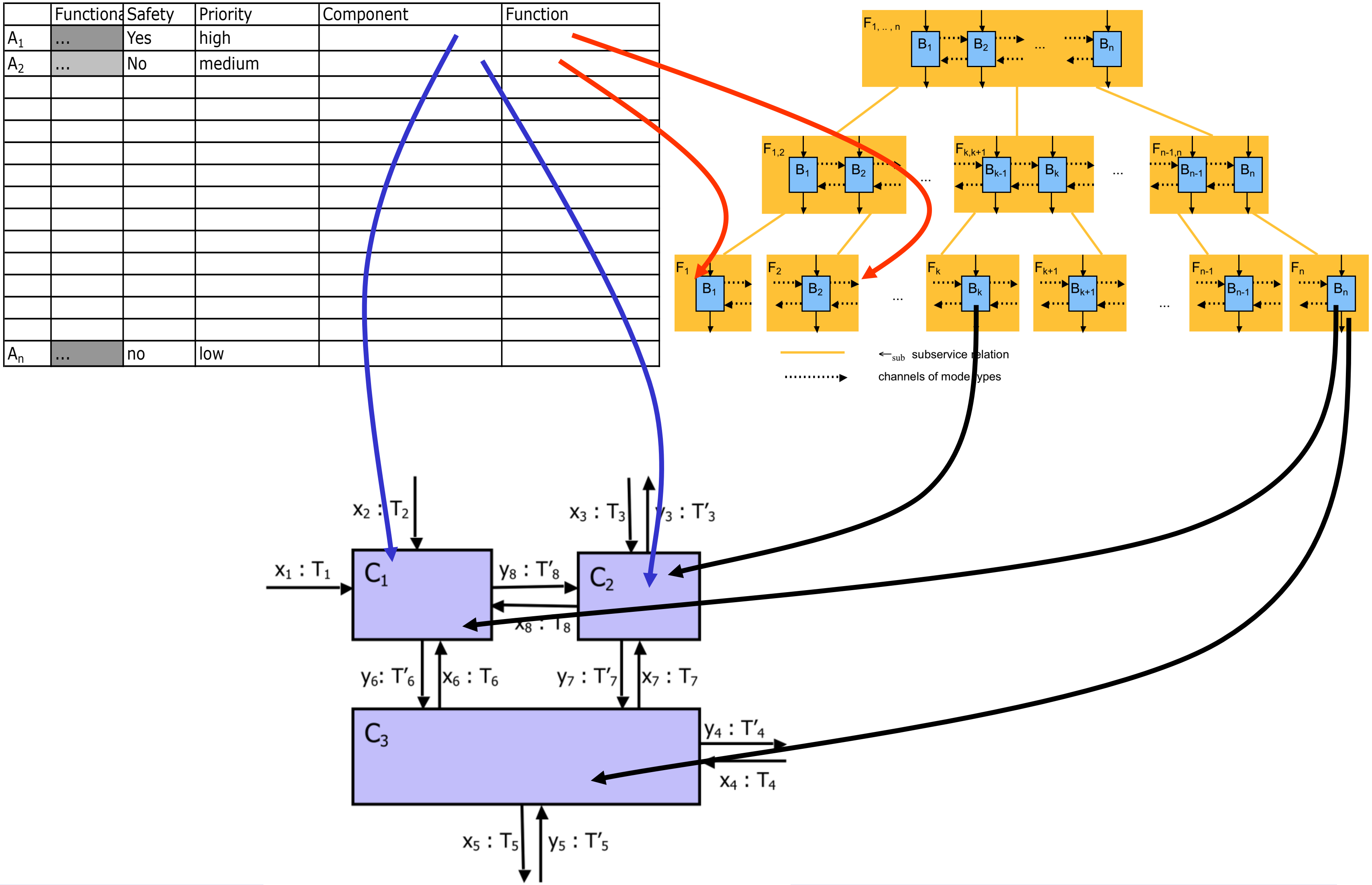
- Correctness
  - ◊ functional specification correct w.r.t to requirements:

$$B \Rightarrow A$$

  - ◊ architecture correct w.r.t to functional spec (let M be the set of mode channels):

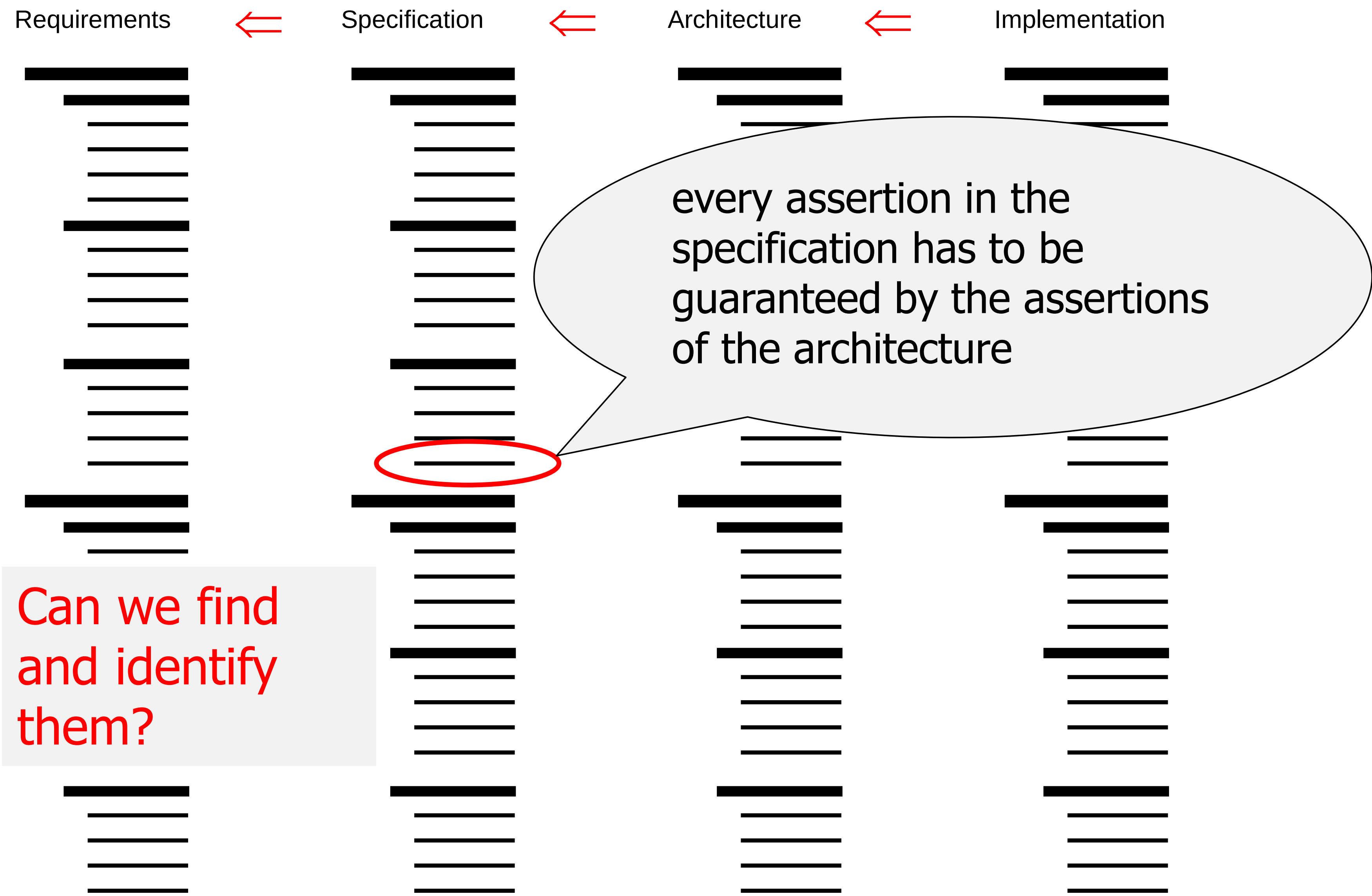
$$C \Rightarrow \exists\ M: B$$

Relational view: Inter-artifact links and traces



	Functiona	Safety	Priority	Component	Function
A_1	...	Yes	high		
A_2	...	No	medium		
A_n	...	no	low		

Illustration: correctness and refinement

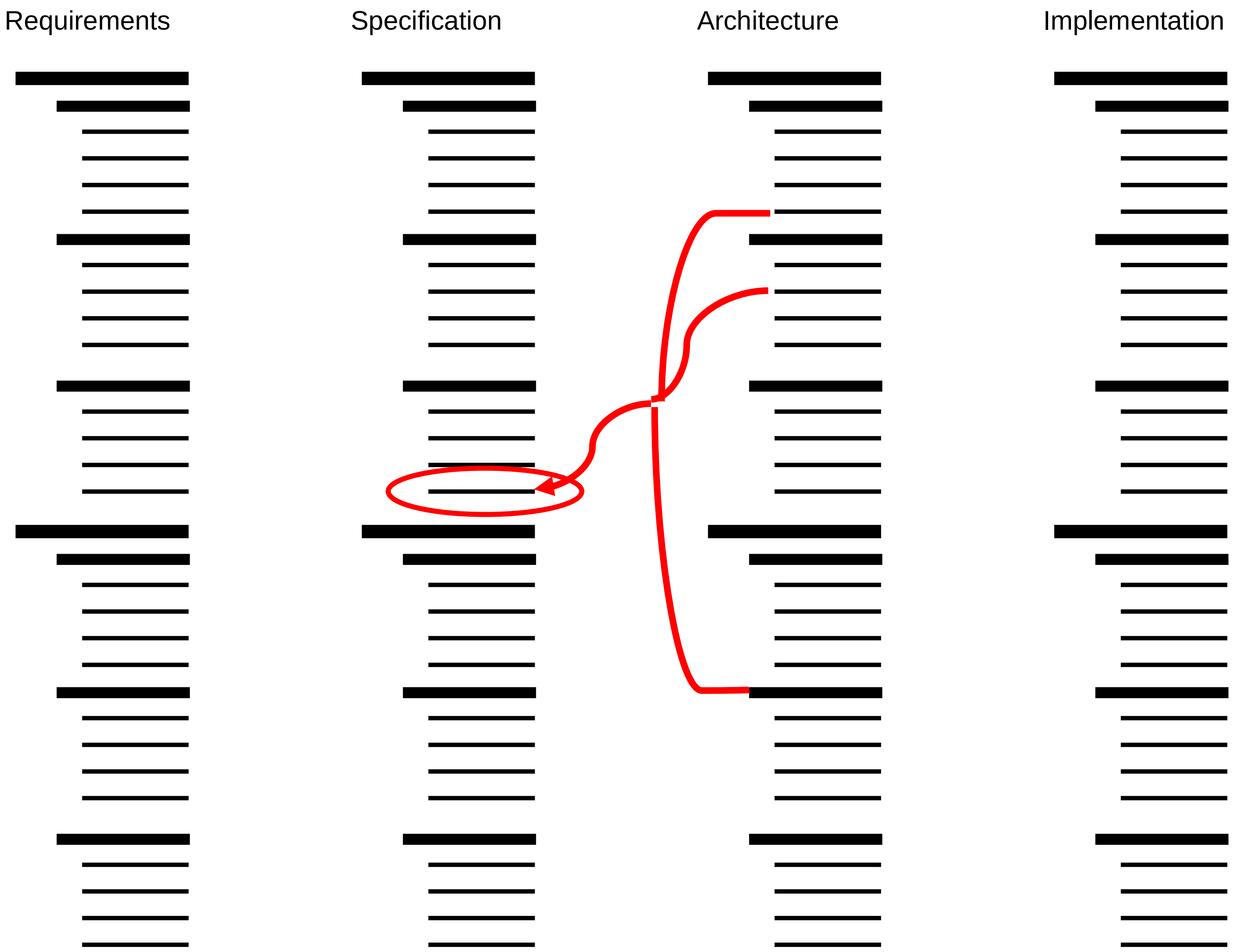


Requirements ⇐ Specification ⇐ Architecture ⇐ Implementation

every assertion in the specification has to be guaranteed by the assertions of the architecture

Can we find and identify them?

Illustration: Multilateral Tracing as refinement



Guarantors and Guarantor Sets

- Let P be an assertion and R be a set of assertions.
- A subset $R' \subseteq R$ is called *guarantor set for* assertion P in set R if

$$\forall((\wedge R') \Rightarrow P)$$

  - ◊ In this case the assertions in set R′ guarantee logically assertion P.
- A guarantor set R′ for assertion P in R is called *minimal*, if every strict subset of set R′ is not a guarantor set for assertion P.
- A minimal guarantor set $R' \subseteq R$ is called *unique* in set R if there do not exist different minimal guarantor sets in R.

Guarantors and Guarantor Sets

- A assertion Q is called *weak guarantor* for assertion $P \in R$ if it occurs in some minimal guarantor set for assertion P in R.
- A assertion Q is called *strong guarantor* for P in R if assertion Q occurs in every guarantor set of assertion P in R.
- Note that there is some relationship between guarantors and the so-called Primimplikanten a la Quine

Relationship: req spec to function spec - tracing

	system level reqs																
	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9			.	.	.			A_k
sub-function reqs																	
B_1	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩
B_2	🟧	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
B_3	🟩	🟧	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩
	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟨	🟩
	🟩	🟩	🟩	🟧	🟩	🟨	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟨	🟩	🟩	🟧	🟩	🟩
…	🟩	🟨	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧
	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩
	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟧	🟧	🟩	🟩
	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟧	🟨	🟩	🟩
	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩
B_n	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟩

Red: B_i is strong guarantor of A_j

Yellow: B_i is weak guarantor of A_j

Green: B_i is not a weak guarantor of A_j

Relationship: architecture to requirements

	system level reqs																
	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9			.	.	.			A_k
sub-system reqs																	
C_1	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
C_2	🟥	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
C_3	🟩	🟥	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩
	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟨	🟩
	🟩	🟩	🟩	🟥	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟨	🟩	🟩	🟥	🟩	🟩
...	🟩	🟨	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥
	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩
	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩
	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟨	🟩	🟩
	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
C_n	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩

Red: C_i is strong guarantor of A_j

Yellow: C_i is weak guarantor of A_j

Green: C_i is not a weak guarantor of A_j

Tracing at a logical level

Requirements	$A = A_1 \wedge A_2 \wedge A_3 \wedge \dots$
Architecture	$C = C_1 \wedge C_2 \wedge C_3 \wedge \dots$
Correctness architecture	$C \Rightarrow A$
Tracing requirement k	$C \Rightarrow A_1 \wedge A_2 \wedge A_3 \wedge \dots \wedge A_k \wedge \dots$
Expanding C	$C_1 \wedge C_2 \wedge C_3 \wedge \dots \Rightarrow A_k$
Weakening C	$(C_1 \Rightarrow C'_1) \wedge (C_2 \Rightarrow C'_2) \wedge (C_3 \Rightarrow C'_3) \wedge \dots$
Such that	$C'_1 \wedge C'_2 \wedge C'_3 \wedge \dots \Rightarrow A_k$

Conclusion:

If the architecture spec C is correct with respect to a particular requirement A_k then there exist assertions C'_i contained in the specifications C_i of the sub-systems of the architectures that guarantee A_k

Analysis

- For every requirement A_k its “guarantors” C'_i are different, in general
  - ◊ Conclusion: Syntactic tracing does not work
- For requirement A_k
  - ◊ there are weakest “guarantors” C'_I
  - ◊ its weakest “guarantors” C'_i are not necessarily unique
  - ◊ many of its “guarantors” C'_i are not necessarily trivial (“true”)
    - There are many links!

Inter-artifact Links: Functional Specification to Requirements

- Relating Functional Specifications to System Level Requirements
  - ◊ The trace concept as introduced above can be used to relate the functional specification B to the requirement specification A.
  - ◊ Due to the specific structure of set B in terms of sub-functions this imposes a specific structure on the set A.
- A requirement Q in A is called *dedicated* functional feature k, if there exist only one strong trace to exactly one feature h with $B_h \in B$.

Inter-Artifact Traces: Relating Architecture to Requirements

- Traces relate content chunks of architectural specification C to the content chunks of system level requirements specification A.
- A requirement Q in A is called *sub-system requirement*, if there exist only one strong trace to exactly one assertion P in C.
  - Then the system level requirement does only affect one subsystem (this is a very special case).

Intra-artifact Links: System Level Requirements Relating Content Chunks of Artifacts by Logic

Well-Formedness of Sets of System Assertions

A set R of system requirements by assertions is called

- *consistent*, if the following proposition holds

  $\exists(\wedge\ R)$

- *non-overlapping*, if (there is a relationship to case distinctions)

  $\forall(\vee\ R)$

- *weakly independent*, if for every pair of non-empty subsets R′, R″ $\subseteq$ R of disjoint non-empty sets of assertions with $Q = \wedge\ R', P = \wedge\ R''$

  $\exists(P \wedge Q)$ P and Q are consistent

  $\exists(\neg P \wedge Q)$ Q does not imply P

  $\exists(P \wedge \neg Q)$ P does not imply Q

Non-overlapping: Sets of assertions forming case distinctions

- We consider a finite set of cases Q_i and a finite set of consequences P_i, $1 \le i \le n$.
- We speak of a complete, disjoint case distinction if both the following two propositions hold

  $\forall \vee \{Q_i: 1 \le i \le n\}$ completeness

  $\forall (Q_i \Rightarrow \neg Q_j)$ for all $i \ne j$ - disjointness

- By these conditions following propositions are equivalent

  $\vee \{Q_i \wedge P_i: 1 \le i \le n\}$ disjunctive normal form

  $\wedge \{Q_i \Rightarrow P_i: 1 \le i \le n\}$ implicative form

- The second form leads to a set $\{(Q_i \Rightarrow P_i): 1 \le i \le n\}$ of assertions that are non-overlapping

Consistency

- Consistency for sets R of assertions

  $$\exists \wedge R$$

- Consistency of two assertions P and Q means $\exists[P \wedge Q]$ which is equivalent to

  $$\neg\forall[P \Rightarrow \neg Q]$$

  $$\neg\forall[Q \Rightarrow \neg P]$$

  which is one of the conditions of logical independence.

- This shows that the fundamental requirement of consistency guarantees two conditions of logical independence.

Analyzing System Level Requirements: Intra-Artifact Links

There are many papers and even standards on the quality of requirements. The IEEE standard Std 830-1998 (see [IEEE 98]) requires the following quality attributes for system and software requirements:

- completeness
- consistency
- unambiguousness/precision
- correctness (more precisely validity)
- understandability/clarity
- traceability
- changeability

Formalization IEEE artifact quality attributes

- Notions from this list such as
  - ◊ completeness
  - ◊ correctness (more precisely validity – the requirement is what the stakeholder meant)
  - ◊ understandability/clarity

  cannot be explicitly addressed in our approach since they have to be analyzed on a different level.
- They deal with properties of requirements that are not captured by our logical relations.

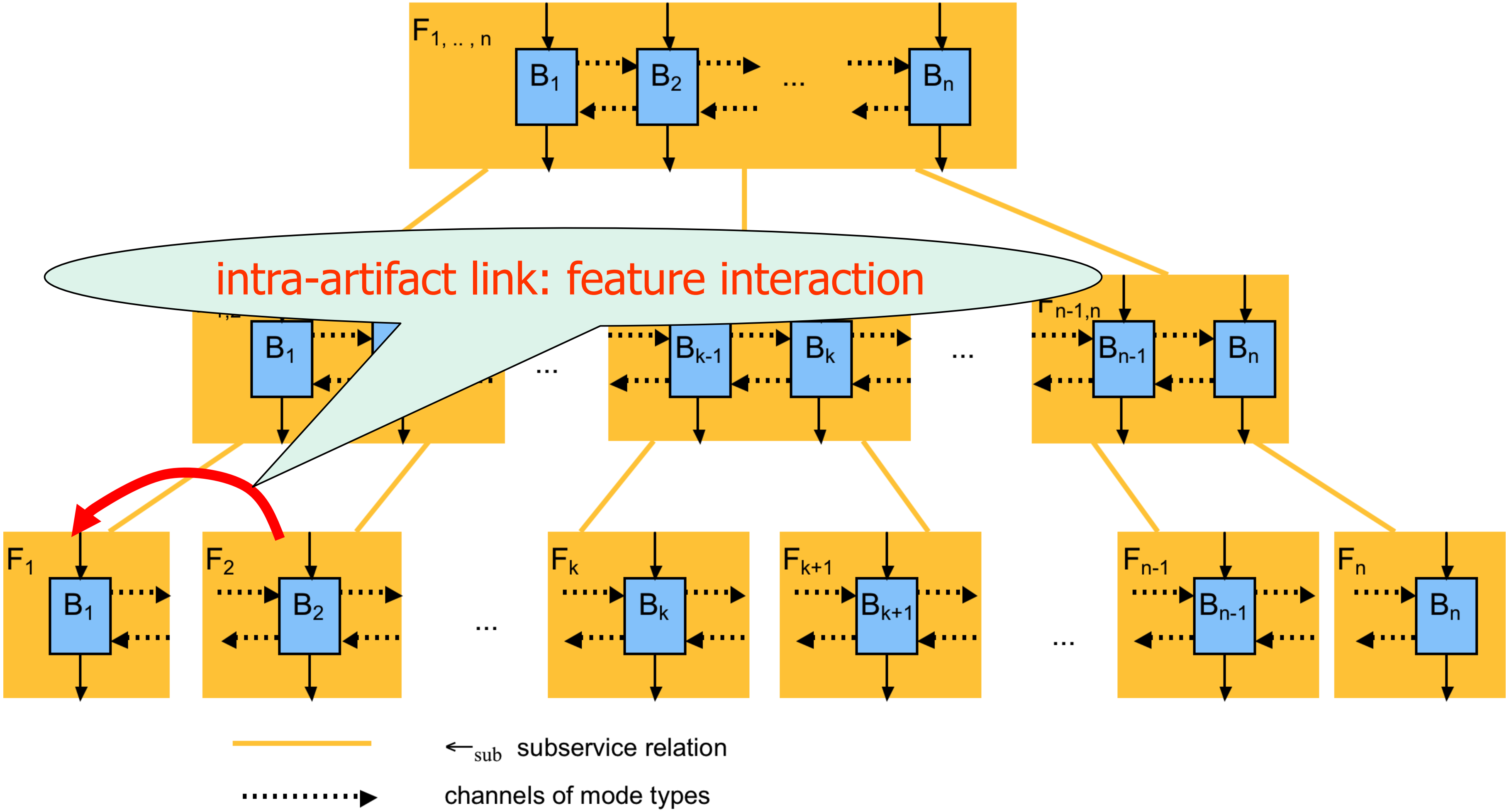
Formalization IEEE artifact quality attributes

- Clarity and understandability is not a formal notion.
  - ◊ depends on the skills and background of the people that read and write specifications.
  - ◊ This quality attribute is beyond our approach of formalization.
- Precision can be achieved by formalization.
- However, quality concepts such as
  - ◊ consistency
  - ◊ traceability
  - ◊ changeability (to some extend)

are captured by our approach.

Intra-artifact Links: Functional System Specification Relating Functional Features by Feature Interactions

Function Hierarchy



Intra-artifact links in functional feature specifications

Given (let be I_1, O_1, I_2, O_2 pairwise disjoint): F Î [I□ O]

(I_1▸O_1) **subtype** (I ▸O) (I_2▸O_2) **subtype** (I ▸O)

there is a feature interaction from the feature

F†(I_2▸O_2) Î [I_2▸O_2] to F†(I_1▸O_1) Î [I_1▸O_1]

if

projection F†(I\\I_2’□ O_1) is not *faithful* in F

Intra-artifact links in functional feature specifications

- If there is a feature interaction from functional feature k to feature k`
  - There exists a mode channel from feature k to feature k`
- If there is a mode channel m from feature k to feature k` and there is no feature interaction from feature k to feature k` then
  - m can be eliminated in the specification of feature k` and the mode channel can be dropped

Intra-artifact Links: Architecture

Analyzing Composition: Intra-Artifact Links and Relations

- Consider two realizable specifications C_1 and C_2 for composable systems with syntactic interfaces $(I_1 \blacktriangleright O_1)$ and $(I_2 \blacktriangleright O_2)$ into a system with syntactic interface $(I \blacktriangleright O)$.
- If specifications C_1 and C_2 are realizable, then $C_1 \wedge C_2$ is a specification for the syntactic interface $(I \blacktriangleright O)$ that is realizable.
- Realizability implies for C_1 and C_2:

  $$\forall I_1 : \exists O_1 : C_1 \qquad \forall I_2 : \exists O_2 : C_2$$
- By composition we derive the specification

  $$\exists Z : C_1 \wedge C_2$$

  where Z is the set of internal channels.
- Note: realizability implies consistency

Analyzing Composition: Intra-Artifact Links and Relations

- If $O_1 \neq \emptyset$ and $O_2 \neq \emptyset$ then C_1 and C_2 are logically independent (if they are not trivial) since

  $$\forall[C_1 \Rightarrow C_2]$$

  $$\forall[C_2 \Rightarrow C_1]$$

  cannot hold due to the fact that C_1 and C_2 talk about disjoint sets of output channels that cannot be constraint by the other assertion.

Intra-Artifact Links for Architecture Specifications

- From the syntactic architecture we conclude which components are connected by channels.
- Channels yield intra-artifact links for architectures.

Note that strictly speaking, there may be channels used as input channels in components that do not depend on that input.

- Then there is a syntactic dependency but not a behavioral dependency
- However, then the channel can be eliminated in the interface assertion

Logical Independence of Functional System Specifications

- The set B consists of assertions being sub-function specifications
  - ◊ Each assertion $B_k \in B$ specifies the interface behavior of a sub-function.
- Assume that these specifications are realizable
  - ◊ As long as all interface assertions $B_k \in B$ for functional features in B are consistent, the set B is consistent, too.
- A simple analysis shows that as long as the interface specifications of the individual functions are not trivial and realizable, the assertions in set B are pairwise
  - ◊ logically independent
  - ◊ consistent

Logical Independence of Functional System Specifications

- Given two interface specifications B_k for syntactic interfaces $(I_k \blacktriangleright O_k)$ and disjoint output sets with $k = 1, 2$ that are realizable we get consistency

  $$\exists(B_1 \wedge B_2)$$

  for free.
- Actually, we should see a functional specification rather as a set of assertions about sub-functions.
- If interface assertions Q_1 and Q_2 for different features are not trivial, i.e. if

  $$\neg\forall Q_1 \text{ and } \neg\forall Q_2$$

  then we get weak independence of the assertions, since they refer to different input channels.

Change Management and Changeability: Impact Analysis for Change Requests

Changeability and Impact Analysis

- Typically, in requirements management we have to revise requirements.
- Requirements are
  - changed and modified
  - validated
  - verified
  - traced
  - implemented
- One essential notion is the granularity of requirements.

Changeability and Impact Analysis

- For validation, refinement, implementation, tracing, and verification a well-chosen granularity of assertions is useful.
  - ◊ If the granularity is too coarse, a further decomposition is needed to address test cases.
  - ◊ If it is too fine too many tests are needed to cover all requirements.
- Typically in requirements engineering we deal with lists of requirements or – more abstractly – with sets R of requirements.

Changeability and Impact Analysis

- Actually, then the ultimate requirement given by the set R is

  $$\wedge R$$

  - ◊ So for the ultimate requirement the granularity of the requirements is not actually relevant.
  - ◊ However, it is relevant for the development activities related to requirements.
- What happens, if we change the granularity of requirements and go from set R with assertions

  $$P, Q \in R \text{ to } R' = (R \setminus \{P, Q\}) \cup \{P \wedge Q\}?$$

  Obviously then

  $$\wedge R \equiv \wedge R'$$

- Thus consistency and validity is not changed.

Concluding Remarks

- Artifacts represented by logic
  - ◊ Logical representation of the content by assertions
- Dependencies based on logic
  - ◊ Logical representation of dependencies
- Formalization of traceability
  - ◊ Intra- and inter-artifact links
- Relating different levels of abstraction
- Engineering questions
  - ◊ How many dependencies are there in systems today
  - ◊ What is the complexity of relations between
    - Requirements and functional specification
    - Functional specification and architecture
    - Requirements and architecture

Next step: variability