Konfigurierbare Systemsoftware (KSS)

VL 2 – Software Product Lines

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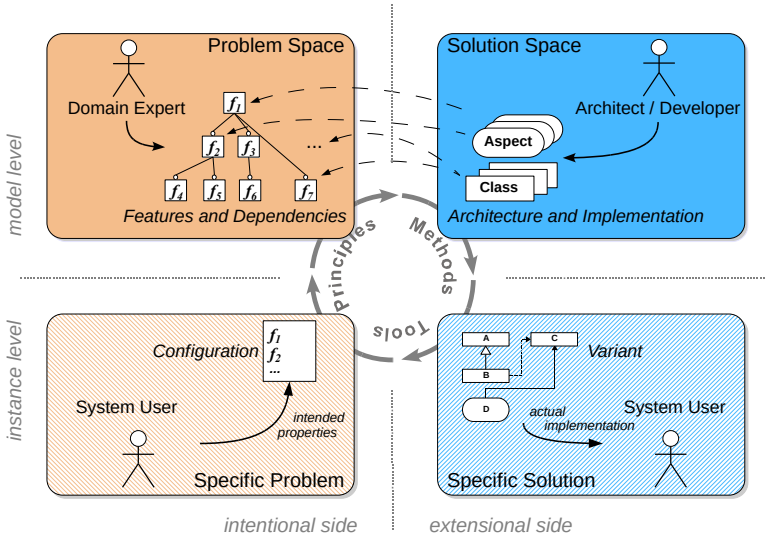
http://www4.informatik.uni-erlangen.de/Lehre/SS15/V_KSS

About this Lecture



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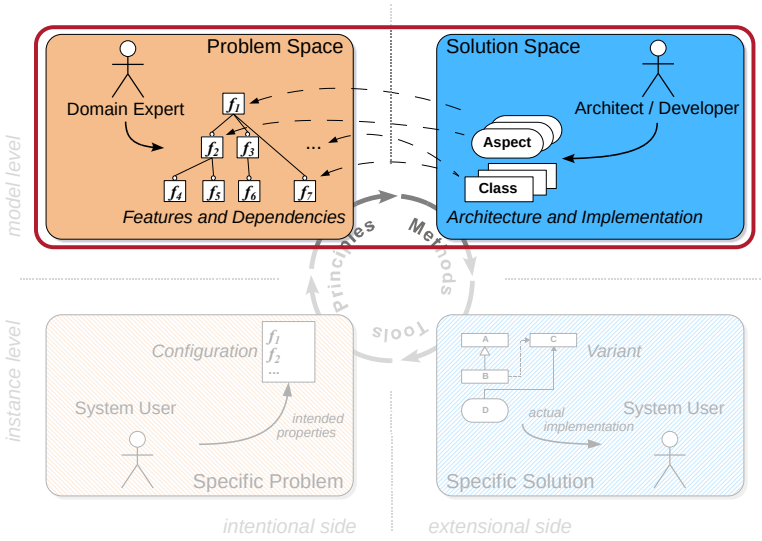


Agenda

Agenda

Model Car Industry: Variety of an BMW X3

- Roof interior: **90000** variants available
- Car door: **3000** variants available
- Rear axle: **324** variants available

> *“ Varianten sind ein wesentlicher Hebel für das Unternehmensergebnis ”*
> Franz Decker (BMW Group)

Model Car Industry: Variety Increase

- **In the 1980s: little variety**
  - Option to choose series and maybe a few extras (tape deck, roof rack)
  - A **single variant** (Audi 80, 1.3l, 55 PS) accounted for **40 percent** of Audi's total revenue
- **Twenty years later: built-to-order**
  - Audi: 10^{20} possible variants
  - BMW: 10^{32} possible variants
  - At average there are 1.1 equal instances of an Audi A8 on the street

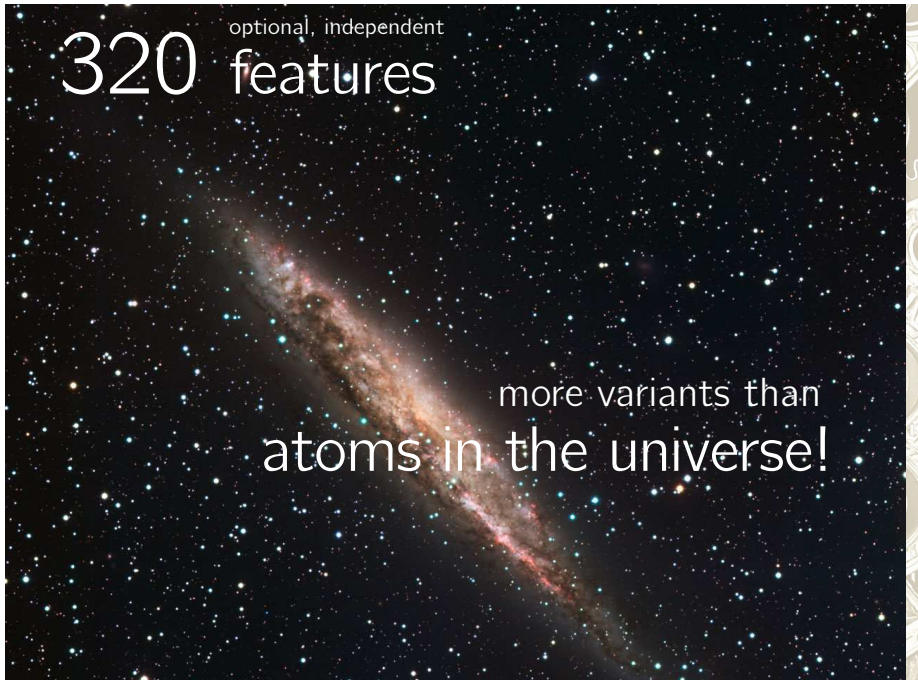
↪ **Product lines** with fully automated assembly

optional, independent

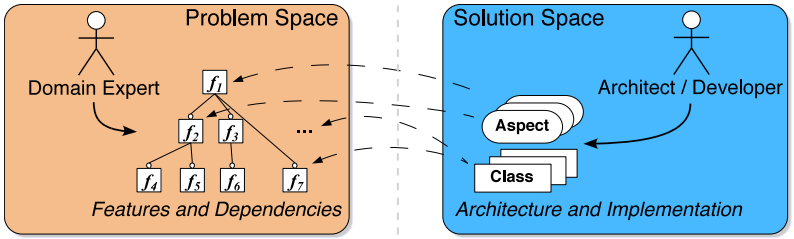
33 features

one individual variant

for each human being



Challenges



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Definition: (Software) Product Line, Feature

Product Line (Withey) (Definition 1)

*“ A **product line** is a group of products sharing a common, managed set of **features** that satisfy the specific needs of a selected **market**. ”*

Withey 1996: *Investment Analysis of Software Assets for Product Lines* [12]

Software Product Line (SEI) (Definition 2)

*“ A **software product line (SPL)** is a set of software-intensive systems that share a common, managed set of **features** satisfying the specific needs of a particular **market** segment or mission and that are developed from a common set of core assets in a prescribed way. ”*

Northrop and Clements 2001: *Software Product Lines: Practices and Patterns* [8]

Remarkable:
SPLs are not motivated by **technical** similarity of the products, but by **feature** similarity wrt a certain **market**

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Feature (Czarnecki / Eisenecker) (Definition 3)

“ A distinguishable characteristic of a concept [...] that is relevant to some stakeholder of the concept. ”

Czarnecki and Eisenecker 2000: *Generative Programming. Methods, Tools and Applications* [3, p. 38]

The Emperors New Clothes?

Program Family (Definition 4)

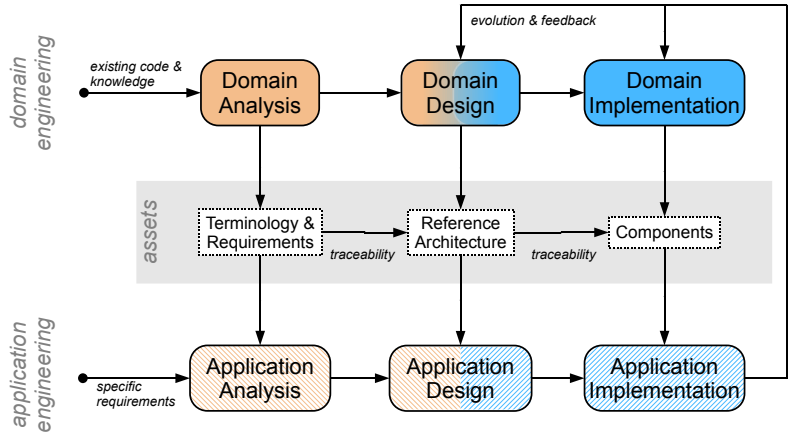
“ Program families are defined [...] as sets of programs whose common properties are so extensive that it is advantageous to study the common properties of the programs before analyzing individual members. ”

Parnas 1976: *“On the Design and Development of Program Families”* [10]

- Most research on operating-system *families* from the ’70s would today qualify as work on software product lines [2, 4, 5, 9–11]
  - Program Family $\rightleftharpoons$ Software Product Line
- However, according to the definitions, the viewpoint is different
  - Program family: defined by similarity between programs $\mapsto$ Solutions
  - SPL: defined by similarity between requirements $\mapsto$ Problems

  $\Rightarrow$ A program family implements a software product line
- In current literature, however, both terms are used synonymously
  - Program Family $\Longleftrightarrow$ Software Product Line

SPL Development Reference Process [1]



application engineering $\mapsto$ **tailoring**

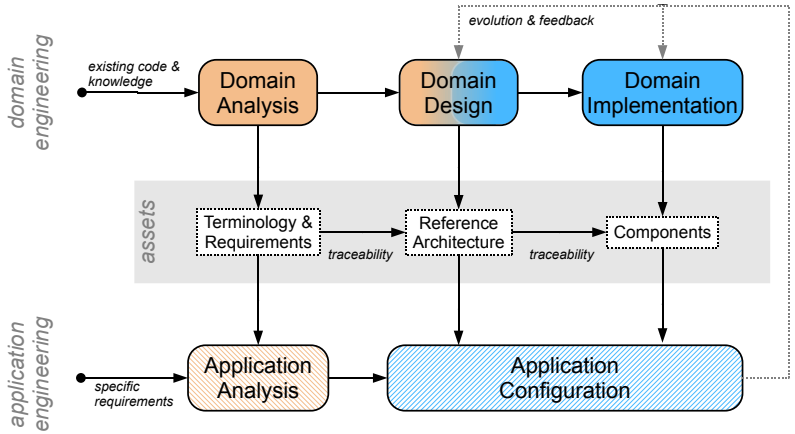
Our understanding: Configurable System Software

Configurability (Definition 5)

Configurability is the property that denotes the degree of pre-defined variability and granularity offered by a piece of system software via an explicit **configuration interface**.

- Common configuration interfaces
  - Text-based: `configure` script or `configure.h` file (GNU tools)
    - configuration by commenting/uncommenting of (preprocessor) flags
    - no validation, no explicit notion of feature dependencies
  - Tool-based: KConfig (Linux, busybox, CiAO, ...), ecosConfig (eCos)
    - configuration by an interactive configuration editor
    - formal model of configuration space, hierarchical features
    - implicit/explicit validation of constraints

Configurable SPL Reference Process

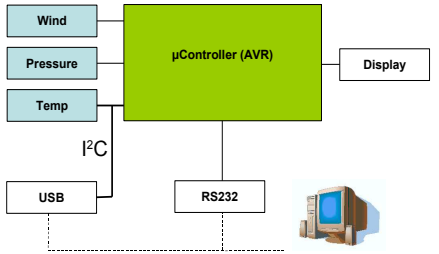


application engineering ↦ **configuring**

Agenda

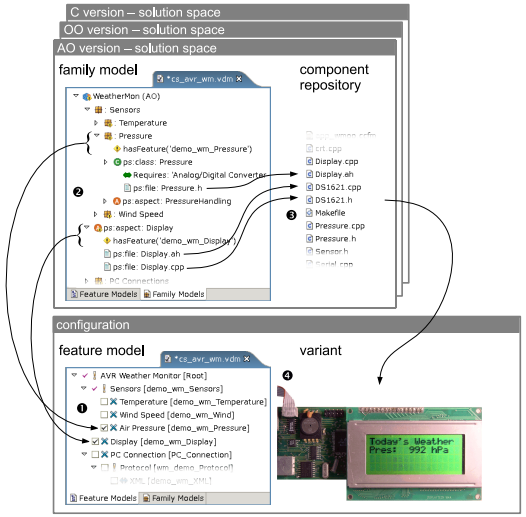
The i4WeatherMon Weather Station [7]

- A typical embedded system
  - Several, optional sensors
    - Wind
    - Air Pressure
    - Temperature
  - Several, optional actuators (here: output devices)
    - LCD
    - PC via RS232
    - PC via USB



- To be implemented as a product line
  - Barometer: Pressure + Display
  - Thermometer: Temperature + Display
  - Deluxe: Temperature + Pressure + Display + PC-Connection
  - Outdoor: <*as above*> + Wind
  - ...

The i4WeatherMon Software Product Line [7]



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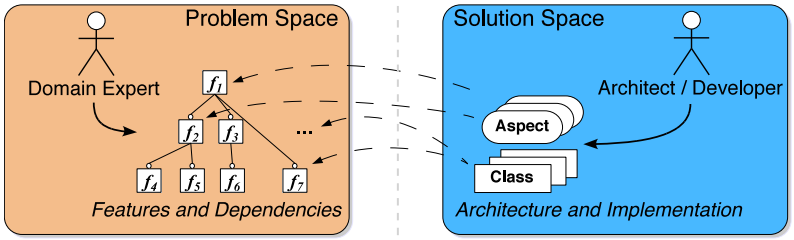

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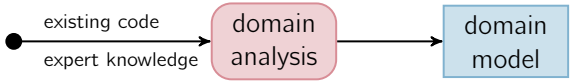
Domain Analysis



- Domain Scoping
  - Selection and processing of domain knowledge
  - Restriction of diversity and variety
- Domain Modelling
  - Systematic evaluation of the gained knowledge
  - Development of a taxonomy

⇝ Domain Model (Definition 6)

*“ A **domain model** is an explicit representation of the **common** and the **variable** properties of the system in a domain, the semantics of the properties and domain concepts, and the dependencies between the variable properties. ”*

Czarnecki and Eisenecker 2000: *Generative Programming. Methods, Tools and Applications* [3]

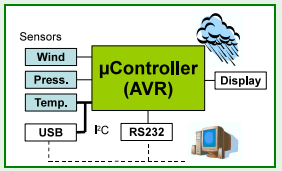
Elements of the Domain Model

- Domain definition specifies the scope of the domain
  - Examples and counter examples
  - Rules for inclusion/exclusion of systems or features
- Domain glossary defines the vocabulary of the domain
  - Naming of features and concepts
- Concept models describe relevant concepts of the domain
  - Formal description (e.g., by UML diagrams)
  - Textual description
  - Syntax and semantics
- Feature models describe the common and variable properties of domain members
  - Textual description
  - Feature diagrams

I4WeatherMon: Domain Model (simplified)

Domain Definition: i4WeatherMon

- The domain contains software for the depicted modular hardware platform. Future version should also support new sensor and actuator types (humidity, alarm, ...).
- The externally described application scenarios thermometer, PC, outdoor, ... shall be supported.



- The i4WeatherMon controller software is shipped in the flash memory of the μC and shall not be changed after delivery.
- The i4WeatherMon shall be usable with all versions of the PC Weather client software.
- ...

I4WeatherMon: Domain Model (simplified)

Domain Glossary: i4WeatherMon

- **PC Connection:** Optional communication channel to an external PC for the sake of continuous transmission of weather data. Internally also used for debug purposes.
- **Sensor:** Part (1 or more) of the i4WeatherMon hardware that measures a particular weather parameter (such as: temperature or air pressure).
- **Actuator:** Part (1 or more) of the i4WeaterMon hardware that processes weather data (such as: LCD).
- **XML Protocol:** XML-based data scheme for the transmission of arbitrary weather data over a PC Connection.
- **SNG Protocol:** Binary legacy data scheme for the transmission of wind, temperature and air pressure data only over a PC Connection. The data scheme is used by versions < 2.0 of PC Weather.
- ...

I4WeatherMon: Domain Model (simplified)

Concept Models: i4WeatherMon

- **XML Protocol:** The following DTD specifies the format used for data transmission over a PC Connection:

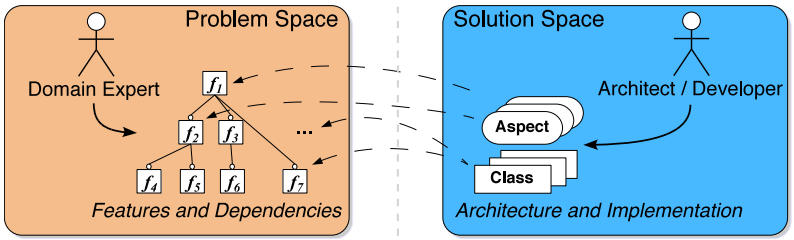
```
<!ELEMEMENT weather ...> ...
```

- **SNG Protocol:** Wind, temperature and air pressure data are encoded into 4 bytes, sequentially transmitted as a 3-byte datagram over a PC Connection as follows:

```
...
```

- **PC Connection** ...
- ...

Challenges



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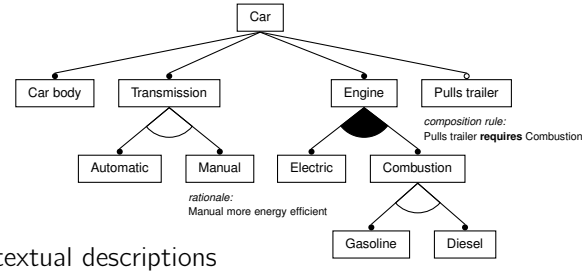
Feature Models

- Describe system variants by their commonalities and differences
  - Specify configurability in terms of optional and mandatory features
  - Intentional construct, independent from actual implementation
- Primary element is the **Feature Diagram**:
  - Concept (Root)
  - Features
  - Constraints

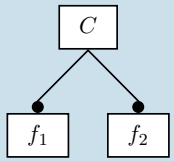


- Complemented by textual descriptions
  - Definition and rationale of each feature
  - Additional constraints, binding times, ...

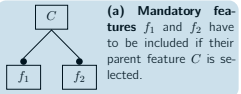
Feature Diagrams – Language [3]

Syntactical Elements

The filled dot • indicates a mandatory feature:
$\mathcal{V} = \{(C, f_1, f_2)\}$



(a) Mandatory features f_1 and f_2 have to be included if their parent feature C is selected.



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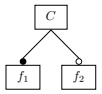
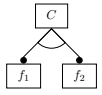
(b) Optional features f_1, f_2 can be included if their parent feature C is selected.



(c) Mandatory feature f_1 has to be included, **optional feature** f_2 can be included if their parent feature C is selected.



(d) Exactly one **alternative feature** f_1 or f_2 has to be included if the group's parent feature C is selected.

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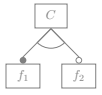
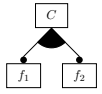


(f) *Not used. Equivalent to* **(e)**.



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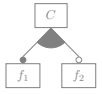

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Feature Diagrams – Language [3]

Syntactical Elements

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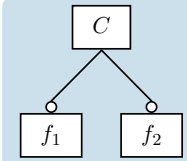

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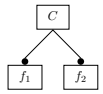

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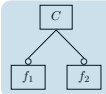

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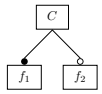

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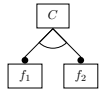

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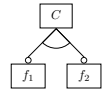

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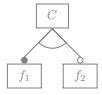

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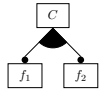

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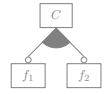

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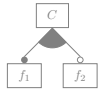

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Feature Diagrams – Language [3]

Syntactical Elements

Of course, both can be combined:
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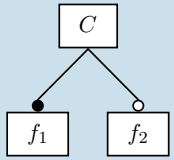

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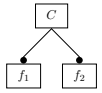

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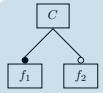

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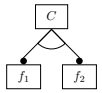

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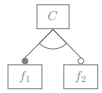

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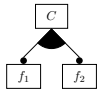

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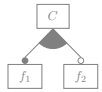

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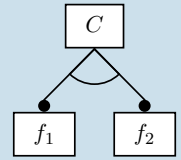
Feature Diagrams – Language [3]

Syntactical Elements

The shallow arc ◺ depicts a group of alternative features:
$\mathcal{V} = \{(C, f_1), (C, f_2)\}$



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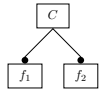

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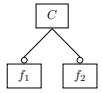

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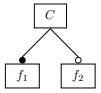

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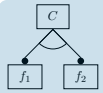

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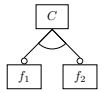

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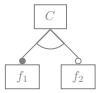
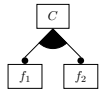


(f) *Not used. Equivalent to* **(e)**.



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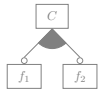
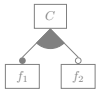


(h) *Not used. Eqivalent to* **(b)**.



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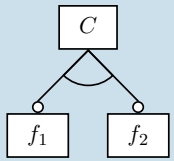
Feature Diagrams – Language [3]

Syntactical Elements

The shallow arc ◺ depicts a group of alternative features:
$\mathcal{V} = \{(C), (C, f_1), (C, f_2)\}$



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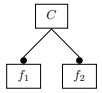

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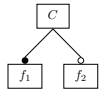

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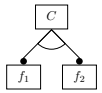

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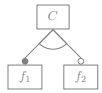
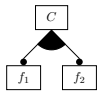


(f) *Not used. Equivalent to* **(e)**.



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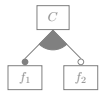

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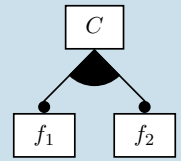
Feature Diagrams – Language [3]

Syntactical Elements

The filled arc ◭ depicts a group of cummulative features: $\mathcal{V} = \{(C, f_1), (C, f_2), (C, f_1, f_2)\}$



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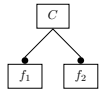

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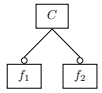

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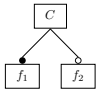

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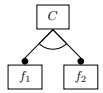

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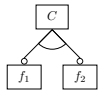

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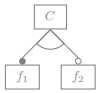
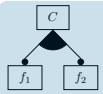


(f) *Not used. Equivalent to* **(e)**.



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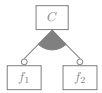
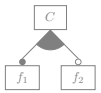


(h) *Not used. Eqivalent to* **(b)**.



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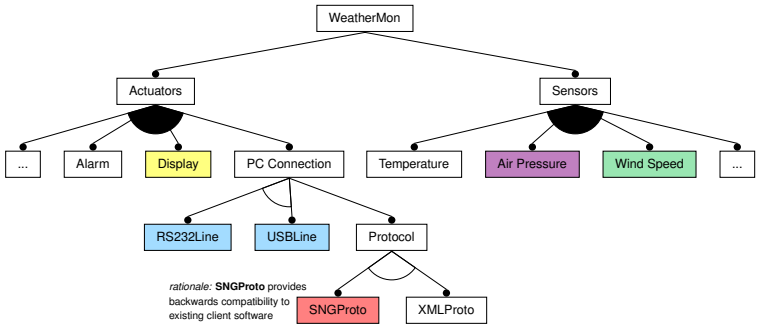
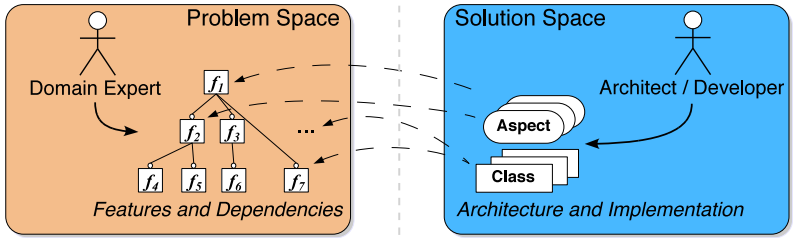
I4WeatherMon: Feature Model



Challenges



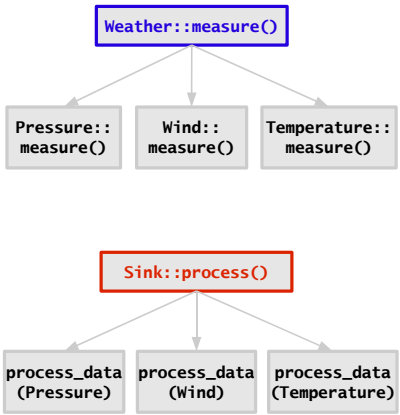
1. How to **identify** the actually desired variability?
2. How to **express** the intended variability?
3. How to **implement** this variability in the code?
4. How to **map** variability options to the code?

Agenda

I4WeatherMon: Reference Architecture

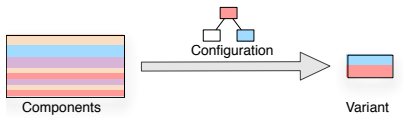
Functional decomposition (structure and process):

```
int main() {
  Weather data;
  Sink    sink;

  while(true) {

    // aquire data
    data.measure();

    // process data
    sink.process( data );

    wait();
  }
}
```



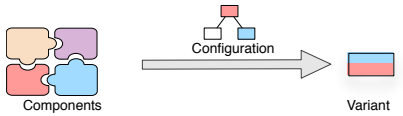
Implementation Techniques: Classification

- Decompositional Approaches



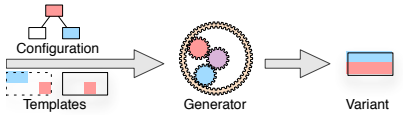
  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches



  - Language-based composition mechanisms (typed)
  - OOP, AOP, Templates

- Generative Approaches



  - Metamodel-based generation of components (typed)
  - MDD, C++ TMP, generators

Implementation Techniques: Goals

General

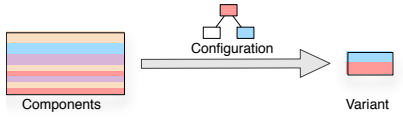
1. Separation of concerns (SoC)
2. Resource thriftiness

Operational

3. **Granularity** Components should be fine-grained. Each artifact should either be mandatory or dedicated to a single feature only.
4. **Economy** The use of memory/run-time expensive language features should be avoided as far as possible. Decide and bind as much as possible at generation time.
5. **Pluggability** Changing the set of optional features should not require modifications in any other part of the implementation. Feature implements should be able to "integrate themselves".
6. **Extensibility** The same should hold for new optional features, which may be available in a future version of the product line.

Implementation Techniques: The C Preprocessor

- Decompositional Approaches

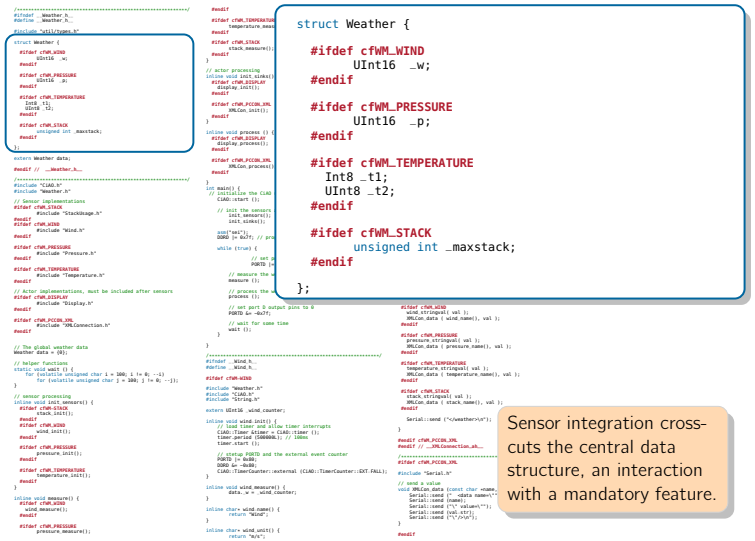


  - Text-based filtering (untyped)
  - Preprocessors (**CPP**)

- Conditional compilation with the C Preprocessor (CPP) is *the* standard approach to implement static configurability [6]
  - Simplicity: the CPP "is just there"
  - Economy: CPP-usage does not involve any run-time overhead
  - Prominent especially in the domain of system software (Linux 3.2: **85000** `#ifdef` Blocks ↦ **"#ifdef hell"**)

I4WeatherMon (CPP): Implementation (Excerpt)

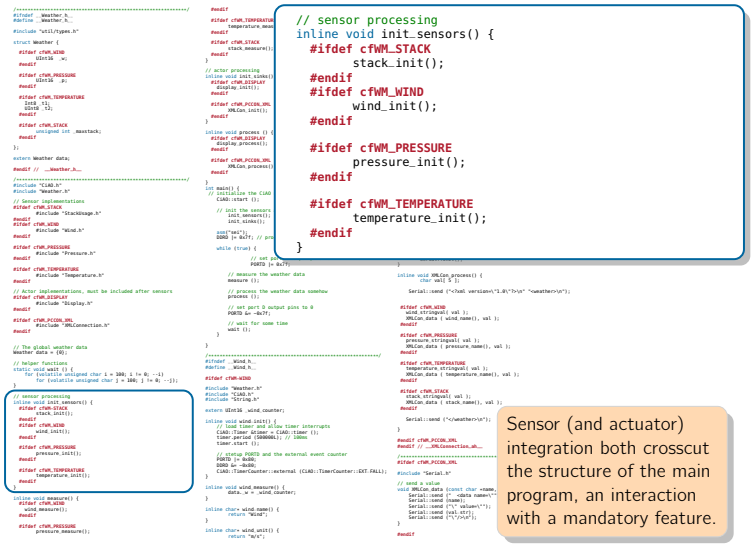
I4WeatherMon (CPP): Implementation (Excerpt)



```
struct Weather {

  #ifdef cfWM_WIND
        UInt16  _w;
  #endif

  #ifdef cfWM_PRESSURE
        UInt16  _p;
  #endif

  #ifdef cfWM_TEMPERATURE
     Int8 _t1;
     UInt8 _t2;
  #endif

  #ifdef cfWM_STACK
        unsigned int _maxstack;
  #endif
};
```

Sensor integration cross-cuts the central data structure, an interaction with a mandatory feature.

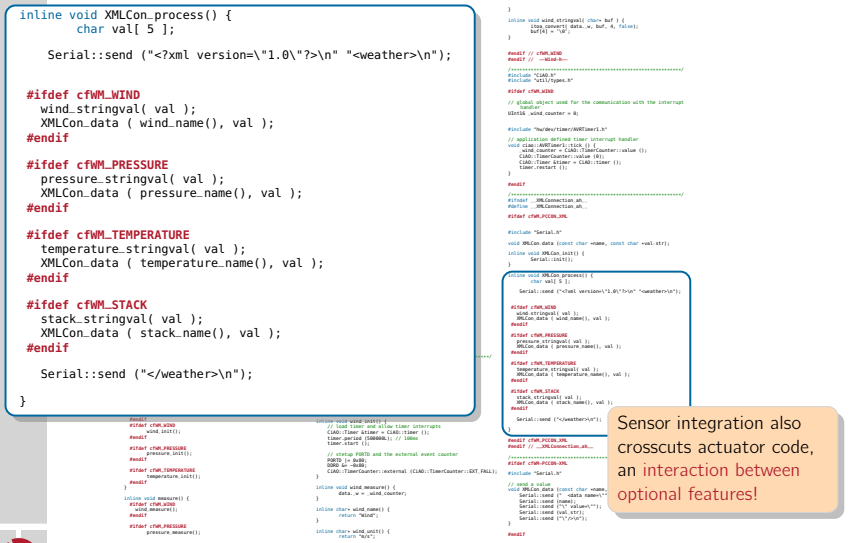
I4WeatherMon (CPP): Implementation (Excerpt)



```
// sensor processing
inline void init_sensors() {
  #ifdef cfWM_STACK
        stack_init();
  #endif
  #ifdef cfWM_WIND
        wind_init();
  #endif

  #ifdef cfWM_PRESSURE
        pressure_init();
  #endif

  #ifdef cfWM_TEMPERATURE
        temperature_init();
  #endif
}
```

Sensor (and actuator) integration both crosscut the structure of the main program, an interaction with a mandatory feature.

I4WeatherMon (CPP): Implementation (Excerpt)



```
inline void XMLCon_process() {
        char val[ 5 ];

    Serial::send ("<?xml version=\"1.0\"?>\n" "<weather>\n");


  #ifdef cfWM_WIND
    wind_stringval( val );
    XMLCon_data ( wind_name(), val );
  #endif

  #ifdef cfWM_PRESSURE
    pressure_stringval( val );
    XMLCon_data ( pressure_name(), val );
  #endif

  #ifdef cfWM_TEMPERATURE
    temperature_stringval( val );
    XMLCon_data ( temperature_name(), val );
  #endif

  #ifdef cfWM_STACK
    stack_stringval( val );
    XMLCon_data ( stack_name(), val );
  #endif

    Serial::send ("</weather>\n");

}
```

Sensor integration also crosscuts actuator code, an interaction between optional features!

I4WeaterMon (CPP): Evaluation

General

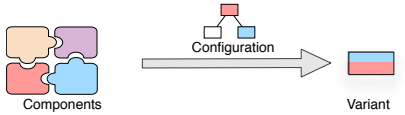
1. Separation of concerns (SoC) ✘
2. Resource thriftiness ✔

Operational

3. Granularity (✔)
   - Components implement only the functionality of a single feature, but contain integration code for other optional features.
4. Economy ✔
   - All features is bound at compile time.
5. Pluggability ✘
   - Sensor integration crosscuts main program and actuator implementation.
6. Extensibility ✘
   - New actuators require extension of main program.
   - New sensors require extension of main program and existing actuators.

Implementation Techniques: OOP

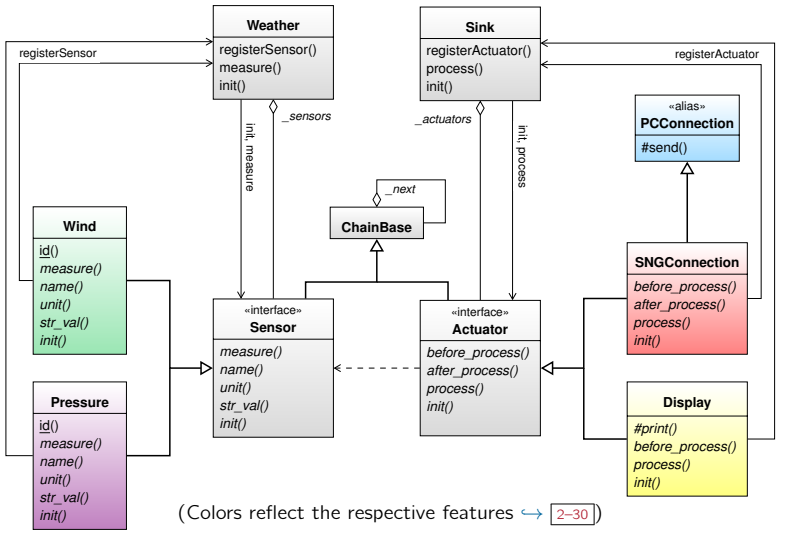
- Compositional Approaches



  - Language-based composition mechanisms (typed)
  - **OOP**, AOP, Templates

- Object-oriented programming languages provide means for loose coupling by generalization and OO design patterns
  - Interfaces
    ⇝ type substitutability (optional/alternative features)
  - Observer-Pattern
    ⇝ quantification (cumulative feature groups)
  - Implicit code execution by global instance construction
    ⇝ self integration (optional features)

I4WeatherMon (OOP): Design (Excerpt)



(Colors reflect the respective features ↪ 2–30)

I4WeaterMon (OOP): Evaluation

General

❶ Separation of concerns (SoC) ✔

❷ Resource thriftiness ?

Operational

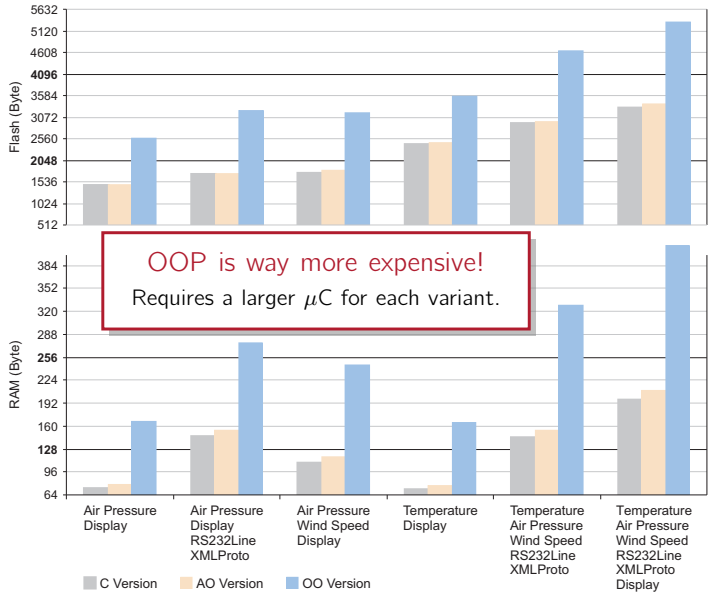
❸ Granularity ✔
- Every component is either a base class or implements functionality of a single feature only.

❹ Economy (✔)
- Run-time binding and run-time type information is used only where necessary to achieve SoC.

❺ Pluggability ✔
- Sensors and actuators integrate themselve by design patterns and global instance construction.

❻ Extensibility ✔
- "Plug & Play" of sensor and actuator implementations.

I4WeaterMon: CPP vs. OOP – Footprint



l4WeaterMon: CPP vs. OOP – Footprint

variant	version	text	data	bss	stack	= flash	= RAM	time (ms)
Air Pressure, Display	**C**	*1392*	*30*	*7*	*34*	*1422*	*71*	*1.21*
	AO	*1430*	*30*	*10*	*38*	*1460*	*78*	*1.21*
	OO	*2460*	*100*	*22*	*44*	*2560*	*166*	*1.29*
Air Pressure, Display,	**C**	*1578*	*104*	*7*	*34*	*1682*	*145*	*60.40*
RS232Line, XMLProto	**AO**	*1622*	*104*	*12*	*38*	*1726*	*154*	*59.20*
	OO	*3008*	*206*	*26*	*44*	*3214*	*276*	*60.80*
Air Pressure, Wind Speed,	**C**	*1686*	*38*	*14*	*55*	*1724*	*107*	*2.96*
Display	**AO**	*1748*	*38*	*18*	*61*	*1786*	*117*	*2.96*
	OO	*3020*	*146*	*33*	*65*	*3166*	*244*	*3.08*
Temperature, Display	**C**	*2378*	*28*	*8*	*34*	*2406*	*70*	*1.74*
	AO	*2416*	*28*	*11*	*38*	*2444*	*77*	*1.73*
	OO	*3464*	*98*	*23*	*44*	*3562*	*165*	*1.82*
Temperature, Wind Speed,	**C**	*2804*	*90*	*17*	*35*	*2894*	*142*	*76.40*
Air Pressure, RS232Line,	**AO**	*2858*	*90*	*23*	*41*	*2948*	*154*	*76.40*
XMLProto	**OO**	*4388*	*248*	*39*	*41*	*4636*	*328*	*76.40*
Temperature, Wind Speed,	**C**	*3148*	*122*	*17*	*57*	*3270*	*196*	*79.60*
Air Pressure, RS232Line,	**AO**	*3262*	*122*	*24*	*63*	*3384*	*209*	*77.60*
XMLProto, Display	**OO**	*5008*	*300*	*44*	*67*	*5308*	*411*	*80.00*

Implementation Techniques: Summary

- CPP: minimal hardware costs – but no separation of concerns
- OOP: separation of concerns – but high hardware costs
- OOP cost drivers
  - Late binding of functions (virtual functions)
    - Calls cannot be inlined (⇝ *memory* overhead for small methods)
    - Virtual function tables
    - Compiler always generates constructors (for vtable initialization)
    - Dead code elimination less effective
  - Dynamic data structures
  - Static instance construction
    - Generation of additional initialization functions
    - Generation of a global constructor table
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Root of the problem:
With OOP we have to use **dynamic** language concepts to achieve loose coupling of **static** decisions.
⇝ **AOP** as an alternative.

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