Part I: Ad-Hoc Approaches for Variability

1. **Introduction**
2. Runtime Variability and Design Patterns
3. Compile-Time Variability with Clone-and-Own

Part II: Modeling & Implementing Features

4. Feature Modeling
5. Conditional Compilation
6. Modular Features
7. Languages for Features
8. Development Process

Part III: Quality Assurance and Outlook

9. Feature Interactions
10. Product-Line Analyses
11. Product-Line Testing
12. Evolution and Maintenance

1a. Introduction to Product Lines

Handcrafting and Customization
Mass Production
Mass Customization
Recap: The Software Life Cycle
Features and Products of a Domain
Software Product Line
Product-Line Engineering
Summary

1b. Challenges of Product Lines

Software Clones
Feature Traceability
Automated Generation
Combinatorial Explosion
Feature Interactions
Continuing Change and Growth
Summary

1c. Course Organization

What You Should Know
What You Will Learn
What You Might Need
Credit for the Slides
Who
Where and When
Taking the Exam, and Beyond
Summary
FAQ

1. Introduction

1a. Introduction to Product Lines

1b. Challenges of Product Lines

1c. Course Organization

What do these examples have in common?

Customization (Maßschneiderung)

- aka. handcrafting
- labor-intensive production
- highly individual goods

Customization of Elevators

two buttons

one button

keyhole

floor display

Customization of Elevators

no button to close door

two keyholes

keycard

double tap for undo

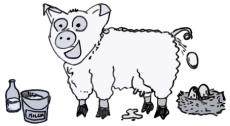
Mass Production

Mass Production (Massenproduktion) [Apel et al. 2013, pp. 3–4]

- consequence of industrialization
- goods are produced from standardized parts
- improved productivity wrt. handcrafting
- reduced costs, improved quality
- but: (almost) no individualism

Principle: One Size Fits All

- t-shirts: XS, S, M, L, XL, XXL
- swiss-army knife (Eierlegende Wollmilchsau)



Mass Production for Software? [Apel et al. 2013, p. 7]

"The idea is to provide software that satisfies the needs of most customers, which leads almost automatically to the situation, in which customers miss desired functionality and are overwhelmed with functionality they do not need actually (just think of any contemporary office or graphics program). It is often this generality that makes software complex, slow, and buggy."

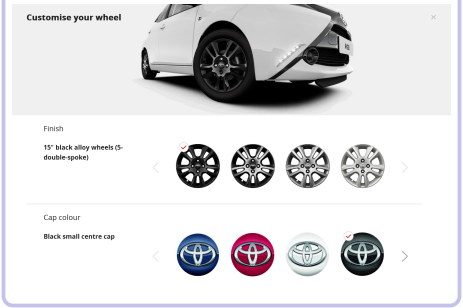
About Every Second Car is Unique

Mass Customization (Kundenindividuelle Massenproduktion)

Mass Customization [Apel et al. 2013, p. 4]

- = mass production + customization
- customized, individual goods at costs similar to mass production

Car Configuration



Car Production

Other Domains

bikes, computers, electronics, tools, medicine, clothing, food, financial services, . . . , software?

Mass Customization for Software?

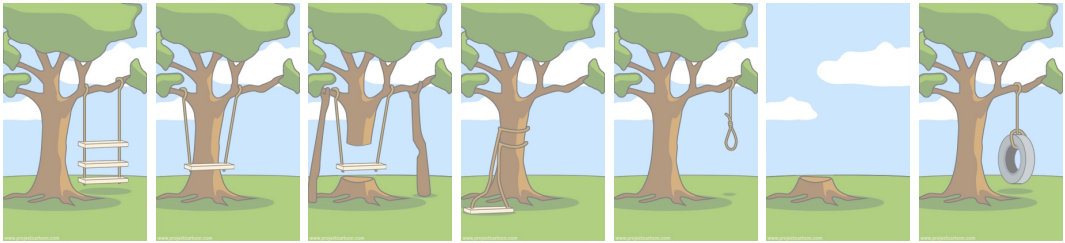
Mass Customization for Software?

- customization: individual software developed using Waterfall model or Scrum
- mass production: standard software developed once for millions or billions of users (e.g., Whatsapp messenger)
- mass customization: software product lines

Why Software Product Lines?

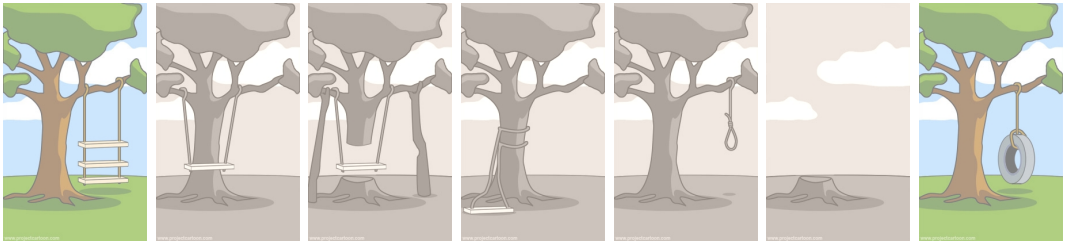
- resource limitations: memory, performance, energy
- different hardware
- different laws
- goal: avoid expensive customization
- how is software developed?

The Project Cartoon



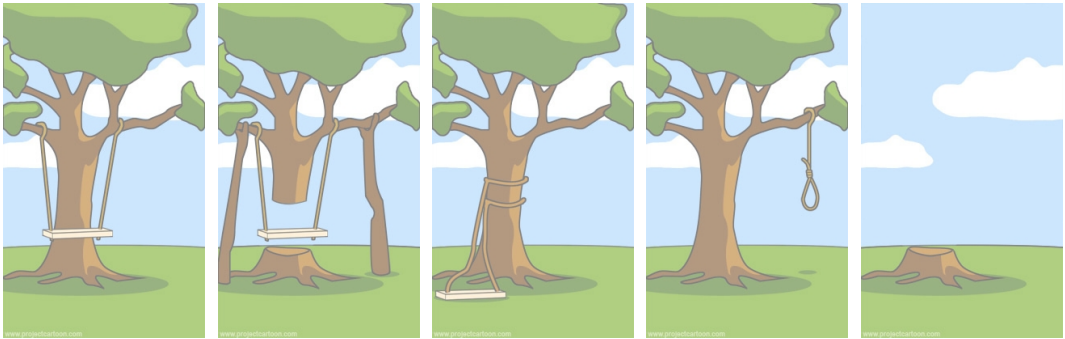
how the customer explained it | how the project leader understood it | how the analyst designed it | how the programmer implemented it | what the beta testers received | how it was supported | what the customer really needed

The Project Cartoon



Requirements | how the project leader understood it | how the analyst designed it | how the programmer implemented it | what the beta testers received | how it was supported | Product

Recap: The Software Life Cycle (Software-Lebenszyklus)

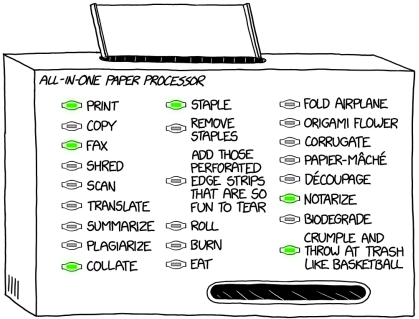


Analysis | Design | Implementation | Testing | Maintenance

What is a Feature?

Feature (Feature) [Apel et al. 2013, p. 18]

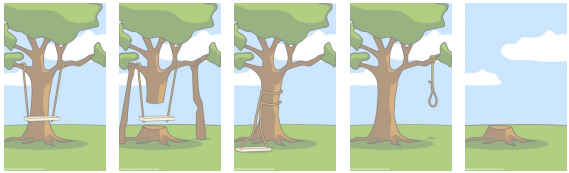
"A **feature** is a characteristic or end-user-visible behavior of a software system."



Feature in a Product Line [Apel et al. 2013, p. 18]

"Features are used in product-line engineering

- to specify and communicate commonalities and differences of the products between stakeholders (Akteure) and
- to guide structure, reuse, and variation across all phases of the software life cycle."



What is a Product?

Product (Produkt) [Apel et al. 2013, p. 19]

"A **product of a product line** is specified by a valid feature selection (a subset of the features of the product line). A feature selection is **valid** if and only if it fulfills all feature dependencies."

Note on Terminology

- in this course:
  product = product variant = variant
- software product: a product consisting only of software
- software is more than a program: requirements, models, source code, tests, documentation
- this course focuses on source code

Product Map for Eclipse (excerpt)

	Java	Enterprise Java/Web	C/C++	Committers
C/C++ Development Tools			✓	
Data Tools Platform		✓		
Git integration for Eclipse	✓	✓	✓	✓
Java Development Tools	✓	✓		✓
Java EE Developer Tools		✓		
JavaScript Development Tools				
Maven Integration for Eclipse	✓	✓		✓

What is a Domain?

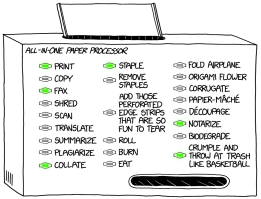
Domain (Domäne) [Apel et al. 2013, p. 19]

"A **domain** is an area of knowledge that:

- is scoped to maximize the satisfaction of the requirements of its stakeholders,
- includes a set of concepts and terminology understood by practitioners in that area,
- and includes the knowledge of how to build software systems (or parts of software systems) in that area."

Features of a Domain

- a feature is a domain abstraction
- identification of features in a domain requires domain expertise
- later: select features for a product line?



Software Product Line

Software Product Line [Northrop et al. 2012, p. 5]

"A **software product line** is

- a set of software-intensive systems

  aka. products or variants

- that share a common, managed set of features

  common set, but not all products have all features in common

- satisfying the specific needs of a particular market segment or mission

  aka. domain (Domäne, Einsatzgebiet, Marktsegment)

- and that are developed from a common set of core assets in a prescribed way."

  aka. planned, structured reuse (Wiederverwendung von vorbereiteten Teilen)

[Software Engineering Institute, Carnegie Mellon University]

Product-Line Engineering

Product-Line Engineering [Pohl et al. 2005, p. 14]

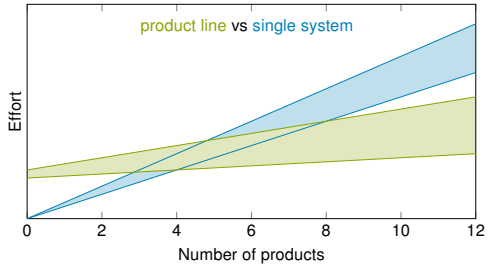
"**Software product-line engineering** is a paradigm to develop software applications (software-intensive systems and software products) using software platforms and mass customization."

Promises of Product Lines [Apel et al. 2013, pp. 9–10]

- tailor-made (Maßschneiderung)
- reduced costs (Kostenreduzierung)
- improved quality (Qualitätssteigerung)
- reduced time-to-market (Reduzierung der Produktentwicklungszeit)

Idea of Product-Line Engineering

Reduce effort per product by means of an up-front investment for the product line:



Single-System Engineering (Einzelsystementwicklung)

classical software development that is not considered as product-line engineering

Introduction to Product Lines – Summary

Lessons Learned

- mass customization
  = mass production + customization
- features, products, domains
- software product lines
- product-line engineering

Further Reading

- Apel et al. 2013, Chapter 1, pp. 3–15 — introduction close to this lecture, further examples
- Northrop et al. 2012, pp. 2–8 — what is not a product line?

Practice

- What other examples of product lines do you know?
- Exemplify the differences between feature, product, domain, and product line for these examples.
- Are these product lines related to software?

1. Introduction

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1b. Challenges of Product Lines

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- Feature Traceability
- Automated Generation
- Combinatorial Explosion
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Software Clones

Software Clone [Rattan et al. 2013, p. 1166]

- = result of copying and pasting existing fragments of the software
- code clones = copied code fragments
- replicates need to be altered consistently
- for example: bugs need to be fixed in all replicated fragments
- in practice: a common source for inconsistencies and bugs

Cloning Parts of Software


Cloning Whole Products (Clone-and-Own)


Feature Traceability

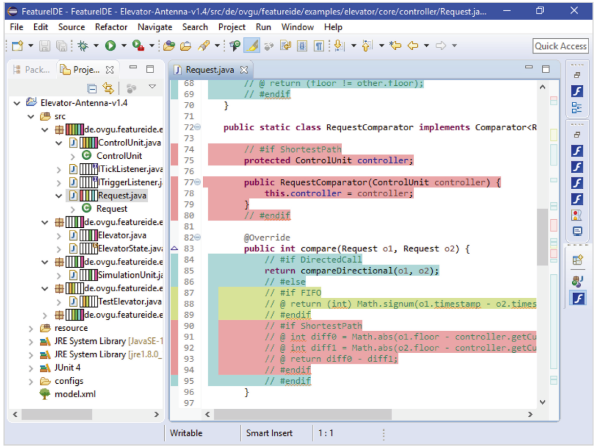
Feature Traceability

Feature traceability is the ability to trace a feature throughout the software life cycle (i.e., from requirements to source code).

Intuition on Feature Traceability

find feature  in product 

Feature Traceability with Colored Source Code

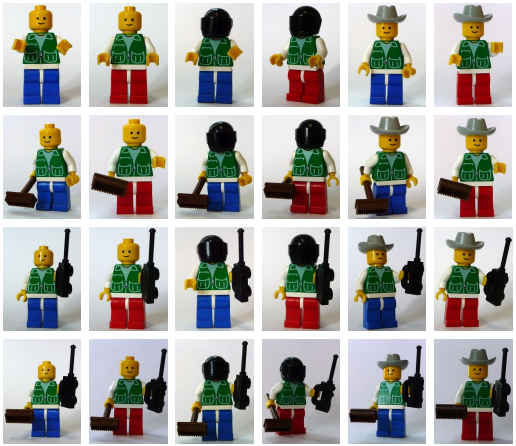


Automated Generation

Features

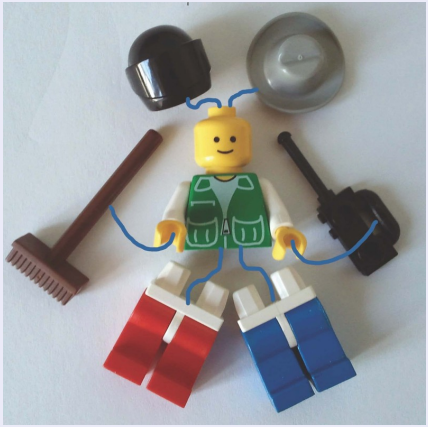
$\Rightarrow$

Products



Automated Generation

Product Line with Features



Goal

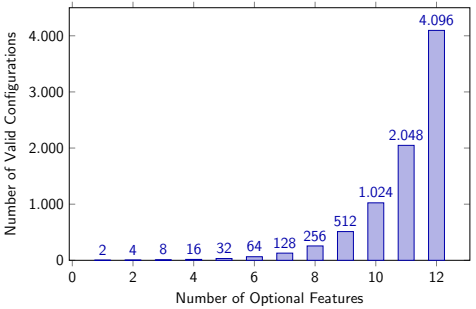
- automatic generation of products
- based on a (descriptive) selection of features

Challenges

- how to map features to source code?
- how to combine source code of multiple features?
- how to define valid combinations of features?

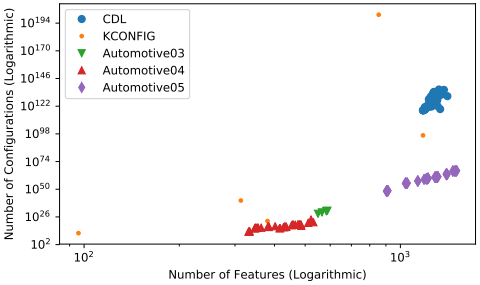
Combinatorial Explosion

Combinatorial Explosion



- assumption: all combinations of features are valid
- 33 features: a unique combination for every human
- 320 features: more combinations than atoms in the universe

Industrial Configuration Spaces [Sundermann et al. 2020]

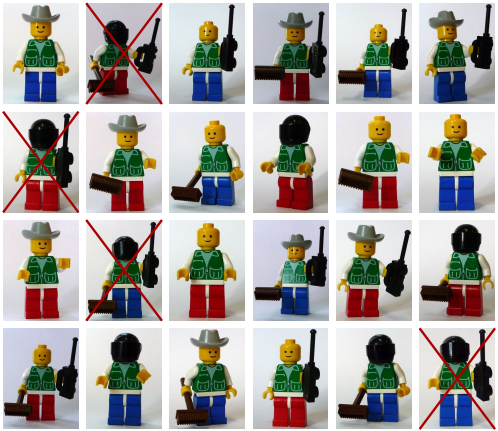


- in practice: not all combinations of features valid
- many industrial product lines too large to specify all valid combinations separately
- largest automotive product line has about $1.7 \cdot 10^{1534}$ products

Combinatorial Explosion

You sell 12467715863077199238873727490314439514330442254979827771939179959
48704895007038086596884750762683178699125554706137139296916402247707623989
44209874897359173593095443687267724538731733090205413699000686174205604563
67918358945723237769032226162401591517046144170618031438553651460038740308
01350065685324847878928481612739525762871421652053586988389048116381601881
76037581684016994400235203403150810331655621013615698057706035390621003047
84859503879593345640078833145636596752961065125514348862370489895791983097
36673417233014005250155052221813897395389431437905641732922313685681317500
13736577090793653032461175202437680317716690037543125535805521623396329598
51136594921793706790008144429927672368215556421058280378775655289115710366
15411765270568810088266268739356230116087196360830692167862459755603055689
84911737263764072946322197760823659018931644830372152412529684198481429399
31845976150777960420140955474136356692610456062245435453098479521665554338
81624352965453269483975729810951995291131521351203210051266848280468625280
93743491549098493785700223513151681610549543583465314724307138800048335461
50908606626583018430487142722274741168056675649788434938634994866281140655
10783811936753647633497463679067687695254056198006082538064697040587889733
81557729554492105622180807407879500664707776577380585585437688717627999998
83391651553343599001454221421034518120990552348929364117299309674386718291
03018536305950720000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000 car variants.

Feature Interactions



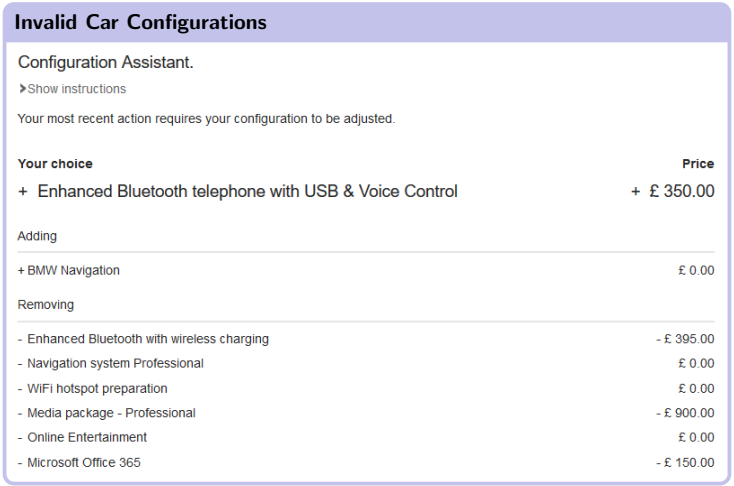
Example Interaction

phone  cannot be used with helmet 

Challenges

- interaction typically unknown in advance
- interactions occur in some but not all combinations
- challenge for quality assurance

Feature Interactions



Continuing Change and Growth

Lehman's Laws of Software Evolution (excerpt) [Lehman et al. 1997]

- Continuing Change: systems must be continually adapted to stay satisfactory
- Increasing Complexity: complexity increases during evolution unless work is done to maintain or reduce it
- Continuing Growth: functionality must be continually increased to maintain user satisfaction
- Declining Quality: quality will decline unless rigorously maintained and adapted to operational environment changes

Essence of the Laws

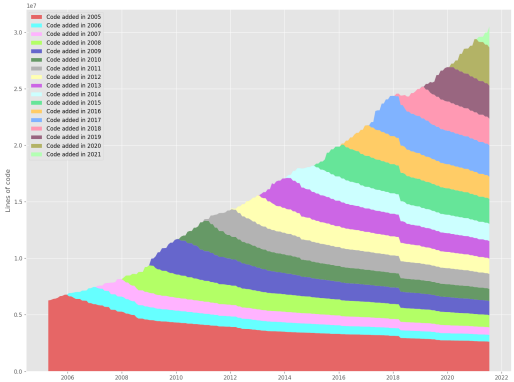
- software that is used will be modified
- when modified, its complexity will increase (unless one does actively work against it)

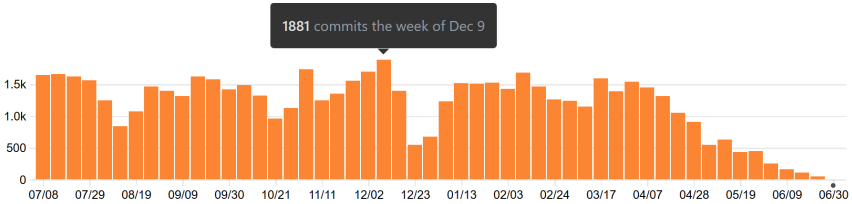
Consequences for Product Lines

- number of features and size of implementation increases over time
- discussed challenges increase over time
  - more software clones
  - harder to trace features
  - automated generation more urgent
  - increasing combinatorial explosion
  - more feature interactions

Evolution of the Linux Kernel

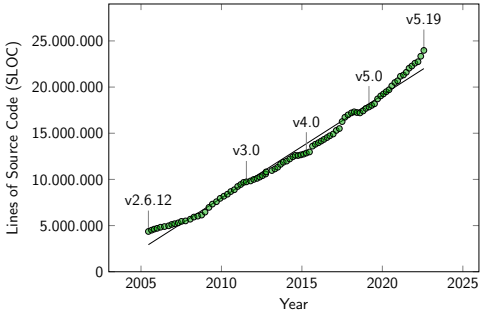
- about 60,000 commits per year
- in peak weeks: new commit every 5 minutes
- in average weeks: every 9 minutes





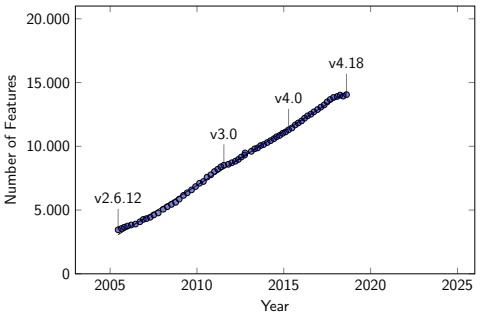
Evolution of the Linux Kernel

Size of the Code Base



- from 4 to 24 millions in 17 years
- about one million LOC added every year
- about 3,000 LOC per day

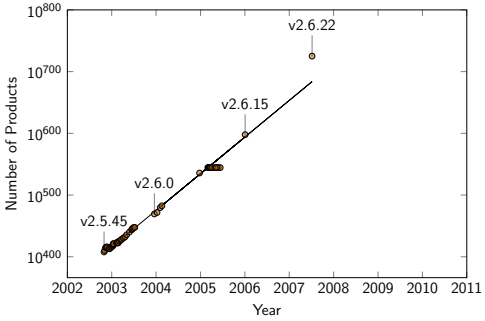
Number of Features



- about 800 new features every year
- about 15 new features every week
- in 2018 four times more features than in 2005

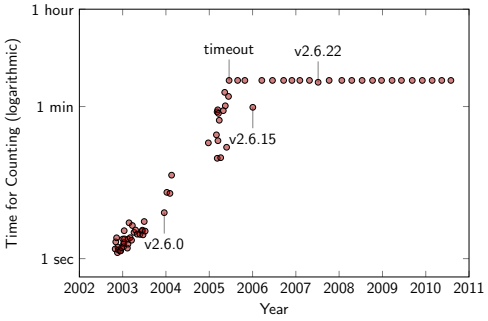
Evolution of the Linux Kernel

Number of Products

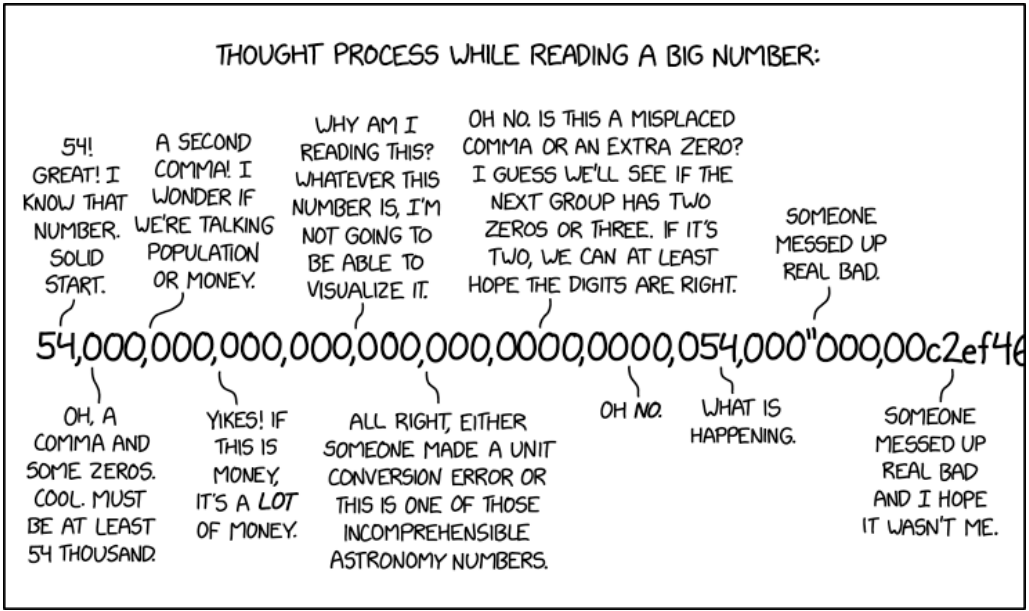


- number of products grows by factor 100.000 each month
- the current kernel is likely to have more than 10^{1500} products

Time to Count Products



- most kernel versions before 2006 can be computed within 1 minute
- most kernel versions after 2006 cannot be computed within 1 hour


THOUGHT PROCESS WHILE READING A BIG NUMBER:
54! GREAT! I KNOW THAT NUMBER. SOLID START.
A SECOND COMMA! I WONDER IF WE'RE TALKING POPULATION OR MONEY.
WHY AM I READING THIS? WHATEVER THIS NUMBER IS, I'M NOT GOING TO BE ABLE TO VISUALIZE IT.
OH NO. IS THIS A MISPLACED COMMA OR AN EXTRA ZERO? I GUESS WE'LL SEE IF THE NEXT GROUP HAS TWO ZEROS OR THREE. IF IT'S TWO, WE CAN AT LEAST HOPE THE DIGITS ARE RIGHT.
SOMEONE MESSED UP REAL BAD.
54,000,000,000,000,000,000,0000,0000,054,000"000,00c2ef46
OH, A COMMA AND SOME ZEROS. COOL. MUST BE AT LEAST 54 THOUSAND.
YIKES! IF THIS IS MONEY, IT'S A LOT OF MONEY.
ALL RIGHT, EITHER SOMEONE MADE A UNIT CONVERSION ERROR OR THIS IS ONE OF THOSE INCOMPREHENSIBLE ASTRONOMY NUMBERS.
OH NO.
WHAT IS HAPPENING.
SOMEONE MESSED UP REAL BAD AND I HOPE IT WASN'T ME.

Challenges of Product Lines – Summary

Lessons Learned

- why are product lines challenging?
- selected challenges:
  1. software clones
  2. feature traceability
  3. automated generation
  4. combinatorial explosion
  5. feature interactions
  6. continuous growth

Further Reading

see later lectures

Practice

- Form groups of 2–3 students
- Explain 2–3 of the six challenges to your colleagues
- Can you find own examples for these challenges?

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1b. Challenges of Product Lines

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What You Should Know

Fundamentals of Software Engineering

- development processes
- object-oriented programming
- design patterns
- UML class diagrams
- modularity

⇒ **Software Engineering**

Fundamentals of Theoretical Computer Science

- set theory
- propositional logic
- complexity theory

⇒ **Logik**
⇒ **Grundlagen der Theoretischen Informatik I**

Exercise

solid programming skills in Java
⇒ **Einführung in die Informatik**
⇒ **Algorithmen und Datenstrukturen**

What You Will Learn

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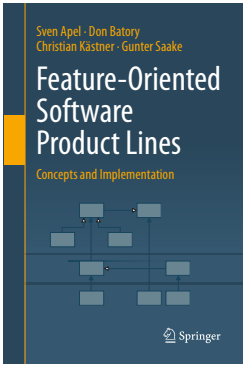
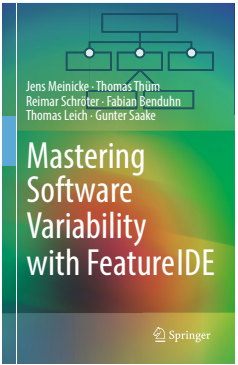
[Apel et al. 2013, Meinicke et al. 2017]

What You Might Need

Recommended Literature for Lecture & Exercise

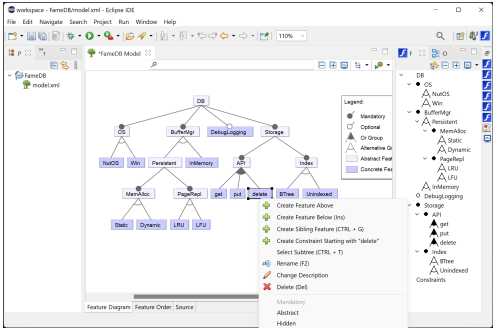


theory-focused



practice-oriented

Recommended Tool Support for the Exercise



IDE FeatureIDE

Credit for the Slides

Thomas Thüm

Professor at TU Braunschweig
software engineering
FeatureIDE team leader

Timo Kehrer

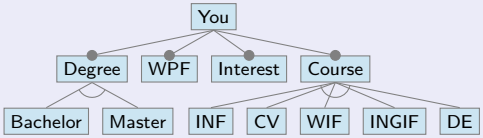
Professor at University of Bern
software engineering

Elias Kuiter

PhD student in Magdeburg
feature-model analysis
FeatureIDE core developer

Who

Who Are You? [Bittner et al. 2019] ;-)



Bachelor $\rightarrow$ ECTS $= 5$
Master $\rightarrow$ ECTS $= 6$

Who

Who Are You?

- a **Bachelor student** (5 ECTS) or
- a **Master student** (6 ECTS)
- looking for an **elective subject** (Wahlpflichtfach (WPF))
- enrolled in **INF**, **CV**, **WIF**, **INGIF**, or **DE**
- interested in
  - **learning** about the basic principles of systematically managing software variability
  - **experimenting** with novel software engineering methods and tools
  - getting in touch with current **research** on software product lines

Who Are We?

Gunter Saake

professor for databases and software engineering

FeatureIDE project manager

Elias Kuiter

PhD student in feature-model analysis

FeatureIDE core developer

Where and When

Lecture

- once per week (2 SWS)
  - on **Monday**, 09:15–10:45
  - starts on October 13
- held by Gunter (+ guests)
- **slides** are available on Moodle
- **guest lectures** planned:
  - industry talk around Christmas
  - research talks at end of January

Exercise

- once per week (2 SWS)
  - on **Tuesday**, 09:15–10:45
  - starts on October 21
- held by Elias
- exercise sheets are available on Moodle
  - **tasks** on each exercise sheet
  - occasional **mandatory tasks**

Taking the Exam, and Beyond

Exam

- oral exam ($\approx$ 20 minutes)
- 1–2 exam days during lecture-free period
- to get an ungraded performance (Schein), you have to pass the exam
- FAQ at the end of each lecture

Exam Eligibility (Prüfungszulassung)

- all mandatory tasks
- 66% of all other tasks (Votierungspunkte)
- 4 presentation points (Vortragspunkte)
- for Master students: programming project
  - develop your own software product line
  - scope of topic is your choice

Further Studies

- **individual and software projects**
- **Bachelor's and Master's theses**

. . . contact us!

Course Organization – Summary

Lessons Learned

- focus: how to implement features
- focus: how to model valid combinations
- focus: how to do quality assurance
- course organization

Further Reading

- Apel et al. 2013 — best book for this lecture
- Meinicke et al. 2017 — more practical guide on tool support

Practice

- Ask questions on the course organization!

FAQ – 1. Introduction

Lecture 1a

- What is a software product line, feature, product/variant, domain?
- What is customization, handcrafting, mass production, mass customization?
- What are example for each of those?
- What is the one-size-fits-all or swiss-army-knife principle? (Eierlegende Wollmilchsau)
- What is the difference between product-line engineering and single-system engineering?
- What are advantages of product-line engineering?

Lecture 1b

- What are software clones, feature traceability, automated generation, combinatorial explosion, feature interactions, and continuous growth?
- Why are those challenging when developing product lines?
- What are examples for these six fundamental challenges?
- How do those challenges interact with each other?
- How complex is the Linux kernel?
- At which pace is the Linux kernel developed?

Lecture 1c

- What you should know?
- What you will learn?
- What you might need?
- Who are the authors of this course?
- How is this course organized?