CS4200-A: Summary & Further Study

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TUDelft

Outline

Compiler Components

- What did we study?

Meta-Linguistic Abstraction

- Another perspective

Domain-Specific Languages

- Applying compiler construction in software engineering

Further Study & Research

- Courses and conferences

Research Challenges

- Including topics for master thesis projects

Exam Dates

Compiler Components

What is a Compiler?

A bunch of components for translating programs

Compiler Components

Parser

- Reads in program text, checks that it complies with the syntactic rules of the language, and produces an abstract syntax tree, which represents the underlying (syntactic) structure of the program.

Type checker

- Consumes an abstract syntax tree and checks that the program complies with the static semantic rules of the language. To do that it needs to perform name analysis, relating uses of names to declarations of names, and checks that the types of arguments of operations are consistent with their specification.

Optimizer

- Consumes a (typed) abstract syntax tree and applies transformations that improve the program in various dimensions such as execution time, memory consumption, and energy consumption.

Code generator

- Transforms the (typed, optimized) abstract syntax tree to instructions for a particular computer architecture. (aka instruction selection)

ChocoPy Compiler

Syntax definition

- Parser through generation, design of abstract syntax

Static semantic analysis

- Name analysis
  - Lexical scoping, type-dependent name resolution
- Type checking
  - Class-based object-oriented language with sub-typing

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Desugaring

- Simple rewrite rules and strategies

Code generation

- Generation of Risc V instructions
- AST-to-AST transformation

Data-flow analysis

- Optimization

CS4200-B

Further Study

More Compiler Components

- Static analyses
- Optimization
- Register allocation
- Code generation for register machines
- Garbage collection

} CS4200-B

Other Object Languages

- Functional programming: first-class functions, laziness
- Domain-specific languages: less direct execution models
- Data (description) languages
- Query languages
- …

Meta-Linguistic Abstraction

Separation of Concerns

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Language design

- Define the properties of a language
- Done by a language designer

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Language implementation

- Implement tools that satisfy properties of the language
- Done by a language implementer

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Language design

- Define the properties of a language
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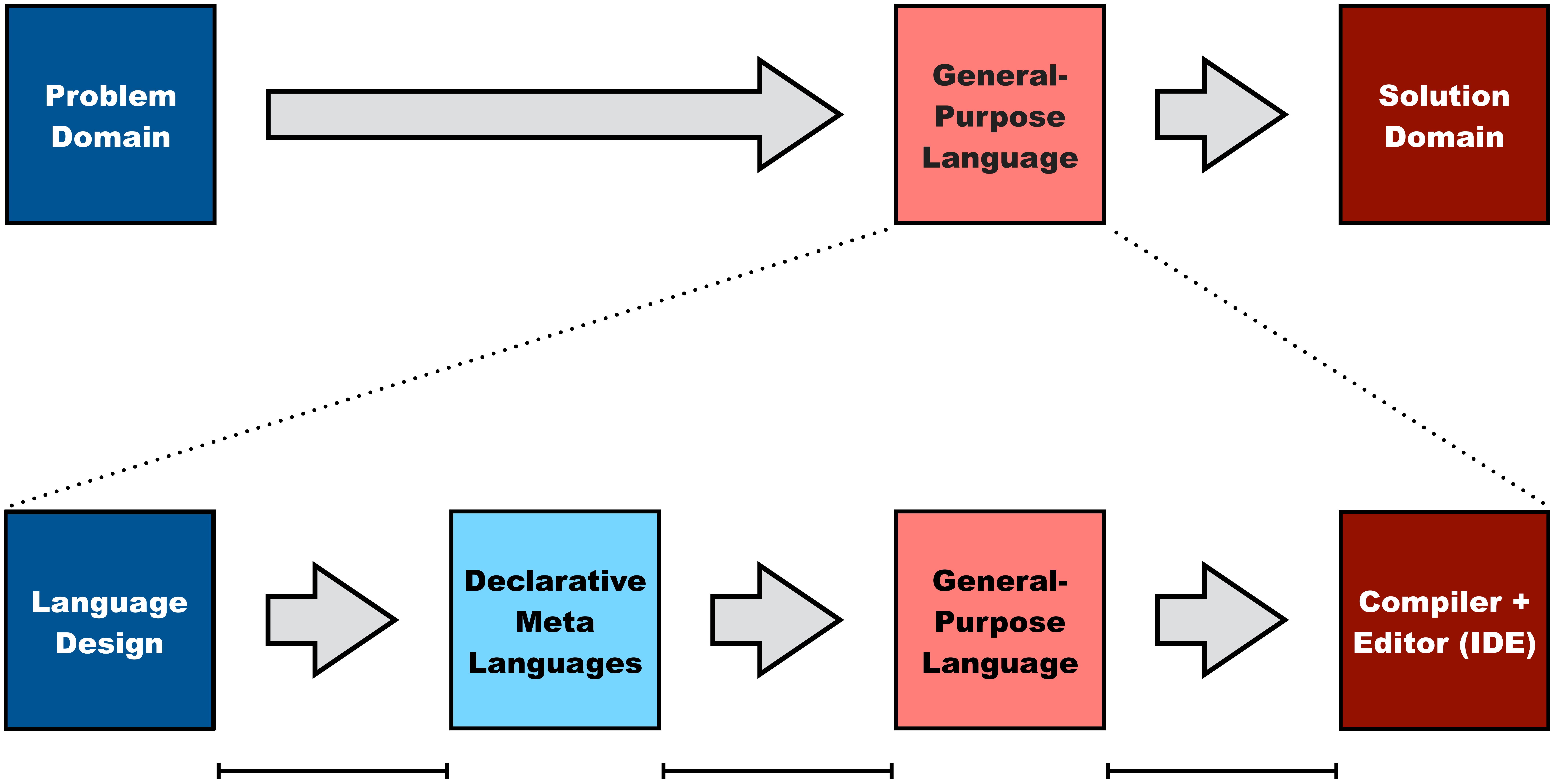
Language implementation

- Implement tools that satisfy properties of the language
- Done by a language implementer

Can we automate the language implementer?

- That is what language workbenches attempt to do



That also applies to the definition of (compilers for) general purpose languages

Declarative Language Definition

Objective

- A workbench supporting design and implementation of programming languages

Approach

- Declarative multi-purpose domain-specific meta-languages

Meta-Languages

- Languages for defining languages

Domain-Specific

- Linguistic abstractions for domain of language definition (syntax, names, types, …)

Multi-Purpose

- Derivation of interpreters, compilers, rich editors, documentation, and verification from single source

Declarative

- Focus on what not how; avoid bias to particular purpose in language definition

Spoofax Meta-Languages

SDF3: Syntax definition
- context-free grammars + disambiguation + constructors + templates
- derivation of parser, formatter, syntax highlighting, …

Statix: Names & Types
- name resolution with scope graphs
- type checking/inference with constraints
- derivation of name & type resolution algorithm

Stratego: Program Transformation
- term rewrite rules with programmable rewriting strategies
- derivation of program transformation system

FlowSpec: Data-Flow Analysis
- extraction of control-flow graph and specification of data-flow rules
- derivation of data-flow analysis engine

DynSem: Dynamic Semantics
- specification of operational (natural) semantics
- derivation of interpreter

} CS4200-A (SDF3, Statix)

} CS4200-B (Stratego, FlowSpec)

PIE: Interactive Software Pipelines

Domain

- Build systems, software pipelines

Design

- Define tasks as functions
- Dynamic dependencies
- Incrementally recompute only tasks affected by a change

Implementation

- Generate Kotlin code
- Run-time dependency analysis

Applications

- Spoofax build, benchmarking pipeline

PIE: Parsing Pipeline

```
typealias In = Serializable; typealias Out = Serializable
interface Func<in I:In, out O:Out> {
  fun ExecContext.exec(input: I): O
}
interface ExecContext {
  fun <I:In, O:Out, F:Func<I, O>> requireCall(clazz: KClass<F>, input: I,
    stamper: OutputStamper = OutputStampers.equals): O
  fun require(path: PPath, stamper: PathStamper = PathStampers.modified)
  fun generate(path: PPath, stamper: PathStamper = PathStampers.hash)
}

class GenerateTable: Func<PPath, PPath> {
  override fun ExecContext.exec(syntaxFile: PPath): PPath {
    require(syntaxFile); val tableFile = generateTable(syntaxFile);
    generate(tableFile); return tableFile
} }
class Parse: Func<Parse.Input, ParseResult> {
  data class Input(val tableFile: PPath, val text: String): Serializable
  override fun ExecContext.exec(input: Input): ParseResult {
    require(input.tableFile); return parse(input.tableFile, input.text)
} }
class UpdateEditor: Func<String, ParseResult> {
  override fun ExecContext.exec(text: String): ParseResult {
    val tableFile = requireCall(GenerateTable::class, path("syntax.sdf3"))
    return requireCall(Parse::class, Parse.Input(tableFile, text))
} }
```

Spoofax 3

Spoofax 3 = Spoofax/PIE

- An implementation of Spoofax with PIE as glue
- Get more live responses
- Under development => bugs! (apologies)

Compiler construction is a lot of fun …

Compiler construction is a lot of fun …

… but when would I ever implement a programming language?

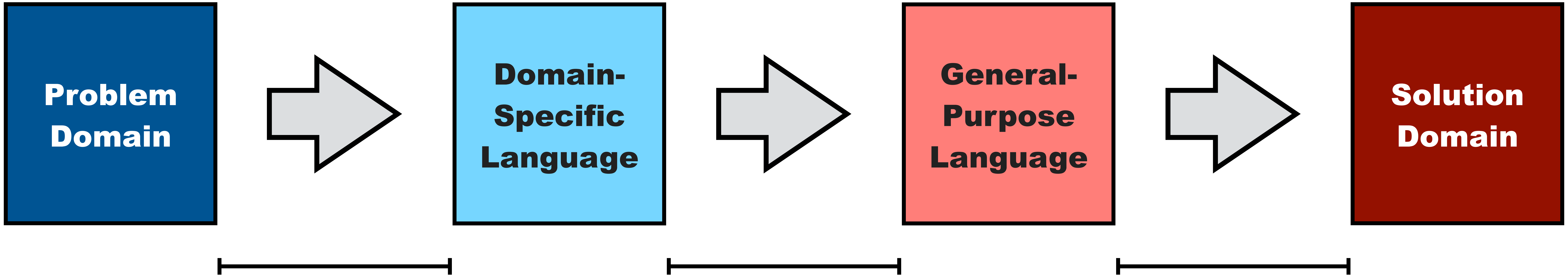
Domain-Specific Languages

Traditional Compiler

Source: high-level machine language

Target: low-level machine language

Domain-Specific Language



Domain-specific language (DSL)

noun

1. a programming language that provides notation, analysis, verification, and optimization specialized to an application domain
2. result of linguistic abstraction beyond general-purpose computation

DSL Compiler

Source: domain-specific language

Target: high-level machine language

Same architecture, techniques as traditional compiler

Green-Marl

Domain

- Graph analytics

Design

- Domain-specific graph traversal, aggregation

Implementation

- Compiler introduces parallel implementation
- Back-ends with different characteristics (parallel, distributed, …)

Applications

- Many graph analytics algorithms such as page rank, …

WebDSL

Domain

- Web programming

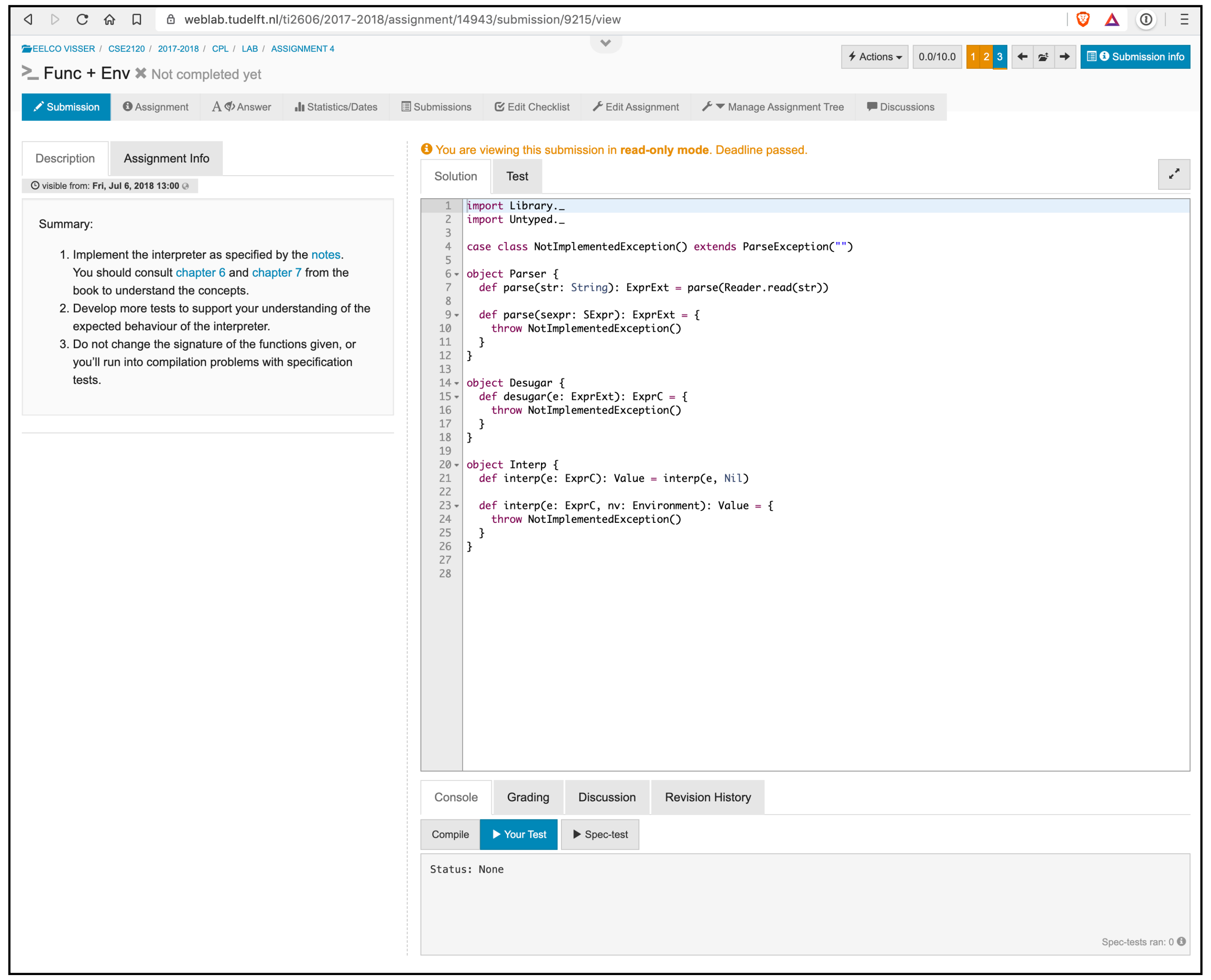
Design

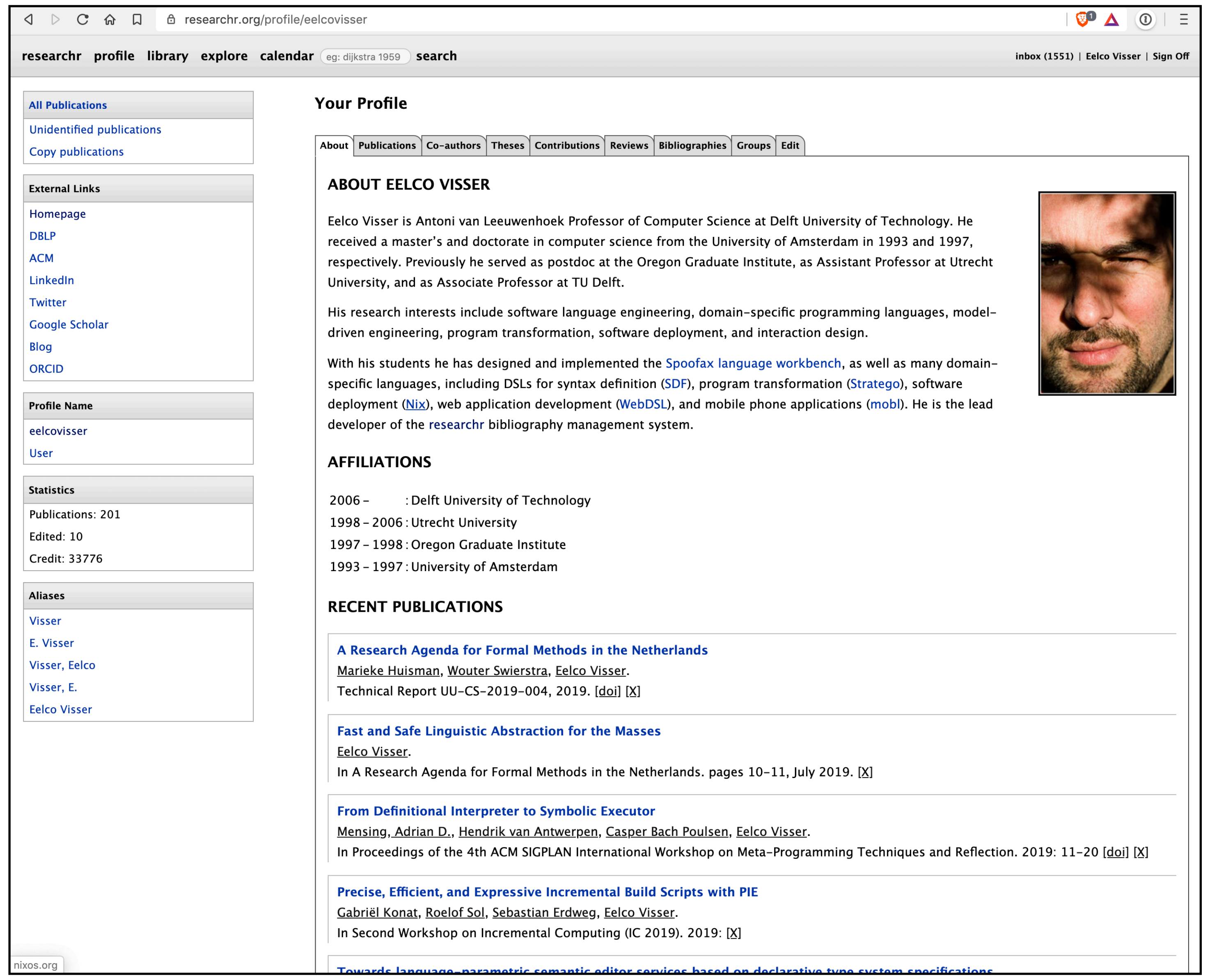
- Sub-languages for sub-domains
    - Entities, Queries, UI (Pages, Templates, Actions), Search, Access Control
- Type checker checks cross-domain consistency

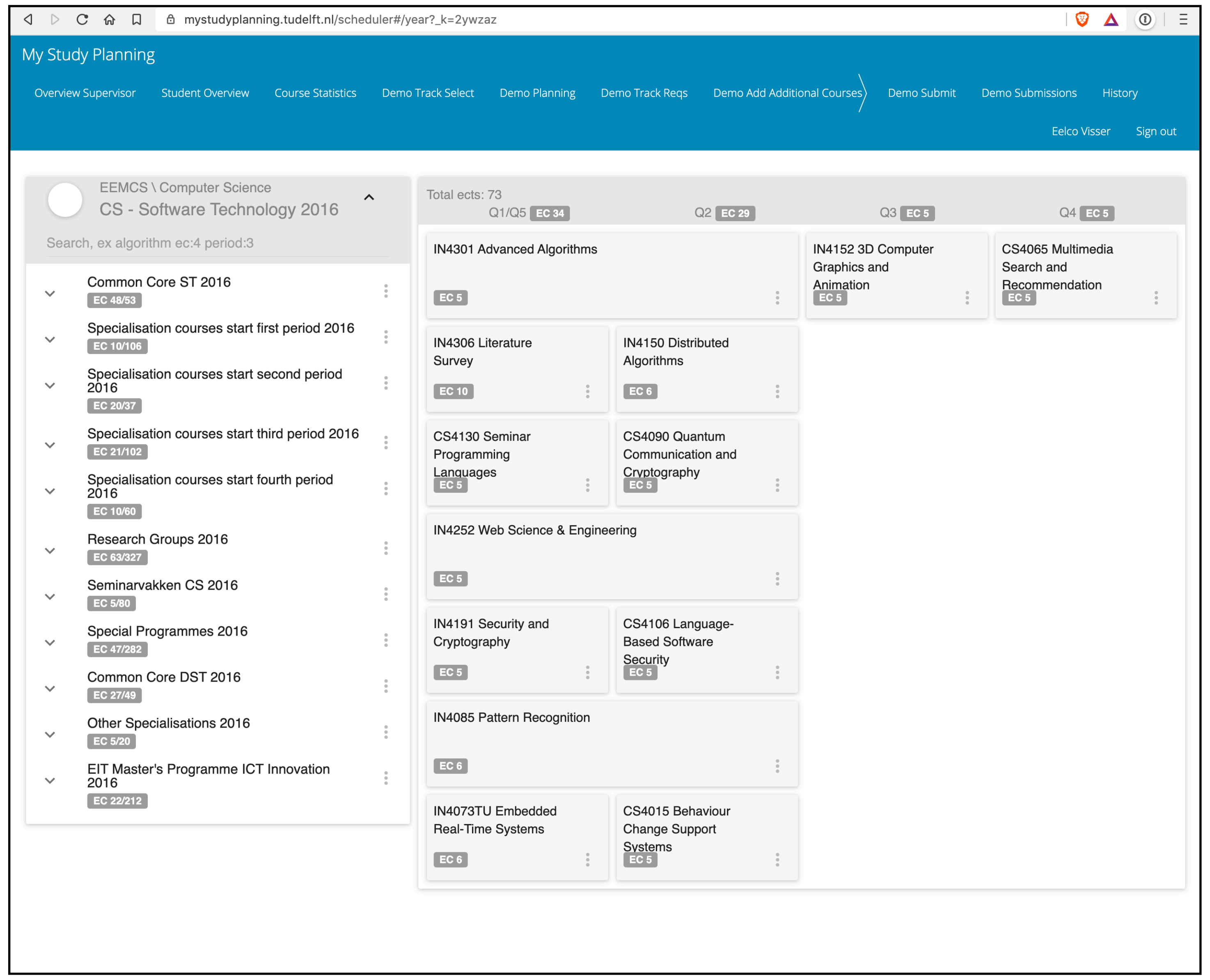
Implementation

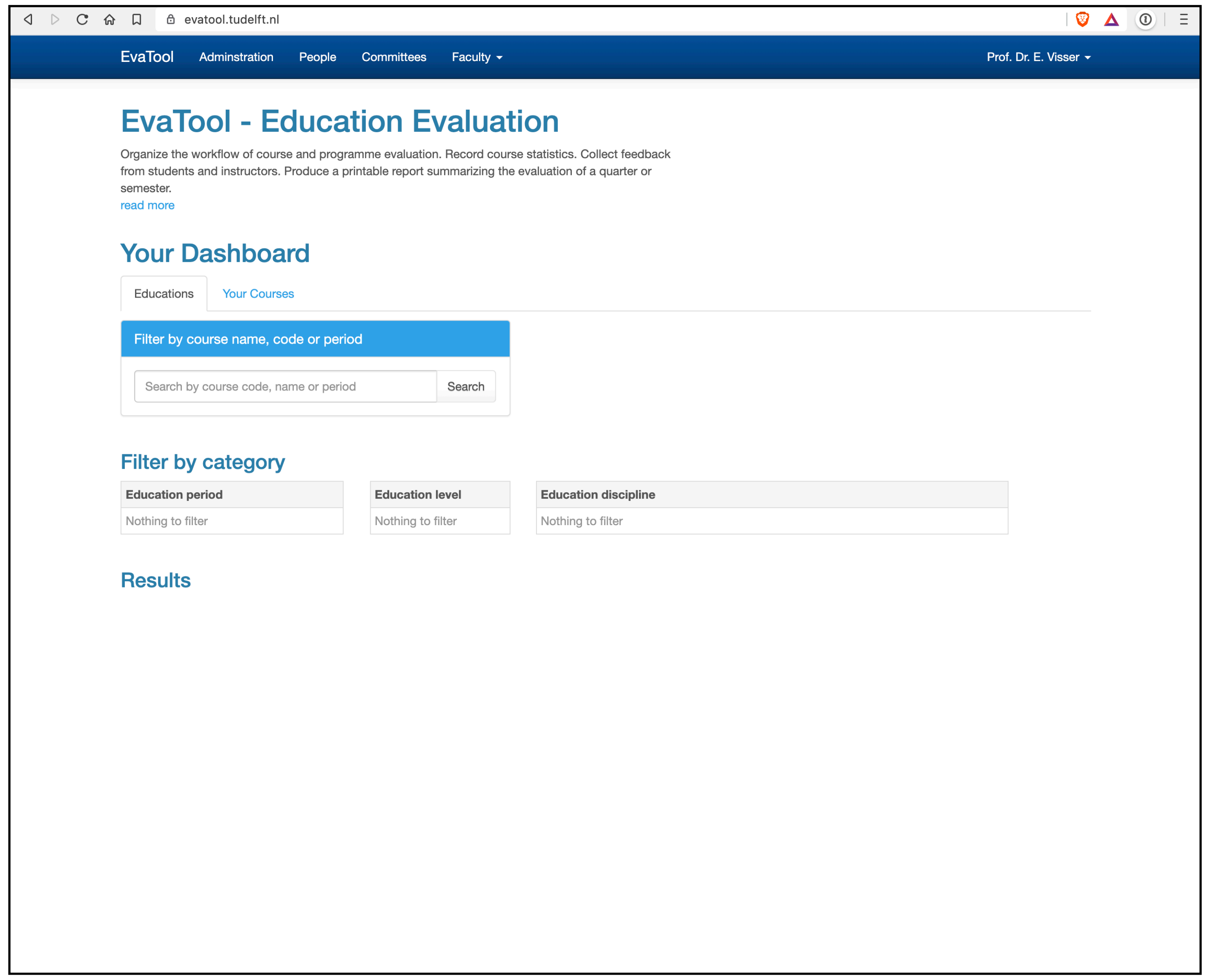
- Generate Java code with web libraries
    - Hibernate (ORM), Lucene (search), …

WebDSL Applications

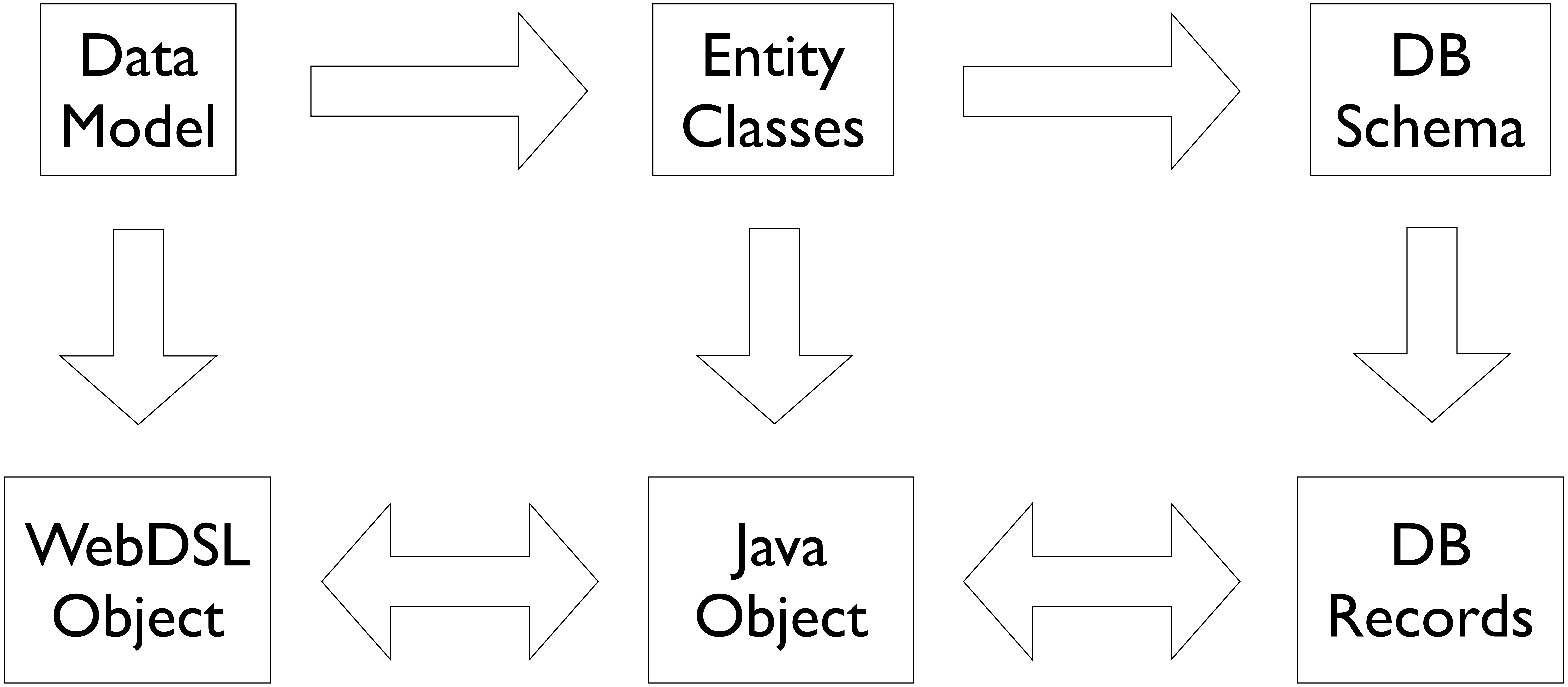








WebDSL: Automatic Persistence



WebDSL: Entity Declarations

entity declaration

property

```
entity E {
  prop :: ValueType
  prop -> EntityType
  prop <> EntityType
  prop -> Set<EntityType>
  prop -> List<EntityType>
  prop -> EntityType (inverse=EntityType.prop)
  function f(x : ArgType) : ReturnType {
    statements;
  }
}
```

WebDSL: Page Definition & Navigation

page navigation (page call)

```
entity A { b -> B }
entity B { name :: String }

define page a(x : A) {
  navigate b(x.b){ output(x.b.name) }
}
define page b(y : B) {
  output(y.name)
}
```

page definition

WebDSL: Templates (Page Fragments)

template definition

```
define main() {
  includeCSS("wiki.css")
  top()
  block[class="content"] {
    elements()
  }
}
define span top() {
  navigate root() {"Wiki"}
}
```

template call

parameter

WebDSL: Forms

```
define page editpage(p : Page) {
  main{
    header{output(p.name) " (Edit)"}
    form{
      input(p.content)
      submit action{ return page(p); } { "Save" }
    }
  }
}
```

data binding

submit

page flow

no separate controller: page renders form *and* handles form submission

WebDSL: Search

search annotations

```
entity Page {
  name         :: String (id,searchable)
  content      :: WikiText (searchable)
  modified     :: DateTime
  authorSearch :: String (searchable) := authorNames()
}

define page search(query : String) {
  var newQuery : String := query;
  form {
    input(newQuery)
    submit action{ return search(newQuery); } {"Search"}
  }
  for(m : Message in searchPage(query, 50)) {
    output(m)
  }
}
```

search queries

WebDSL: Validation Rules

data validation

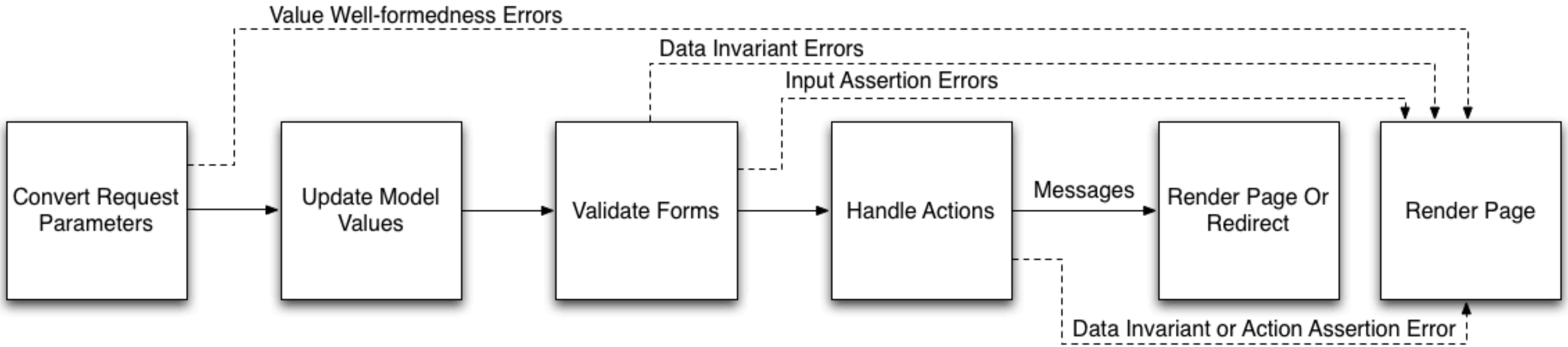
```
entity E {
  validate(c, m)
  prop :: t (validate(c, m))
}

define t() {
  input(x) { validate(c, m) }
  action a() { validate(c, m); message(m); }
}
```

form validation

action assertions

messages

WebDSL: Data Validation Lifecycle



WebDSL: securityContext

```
entity User {
  username  :: String (id)
  fullname  :: String (name)
  email     :: Email
  password  :: Secret
}

access control rules

  principal is User with credentials username, password
```

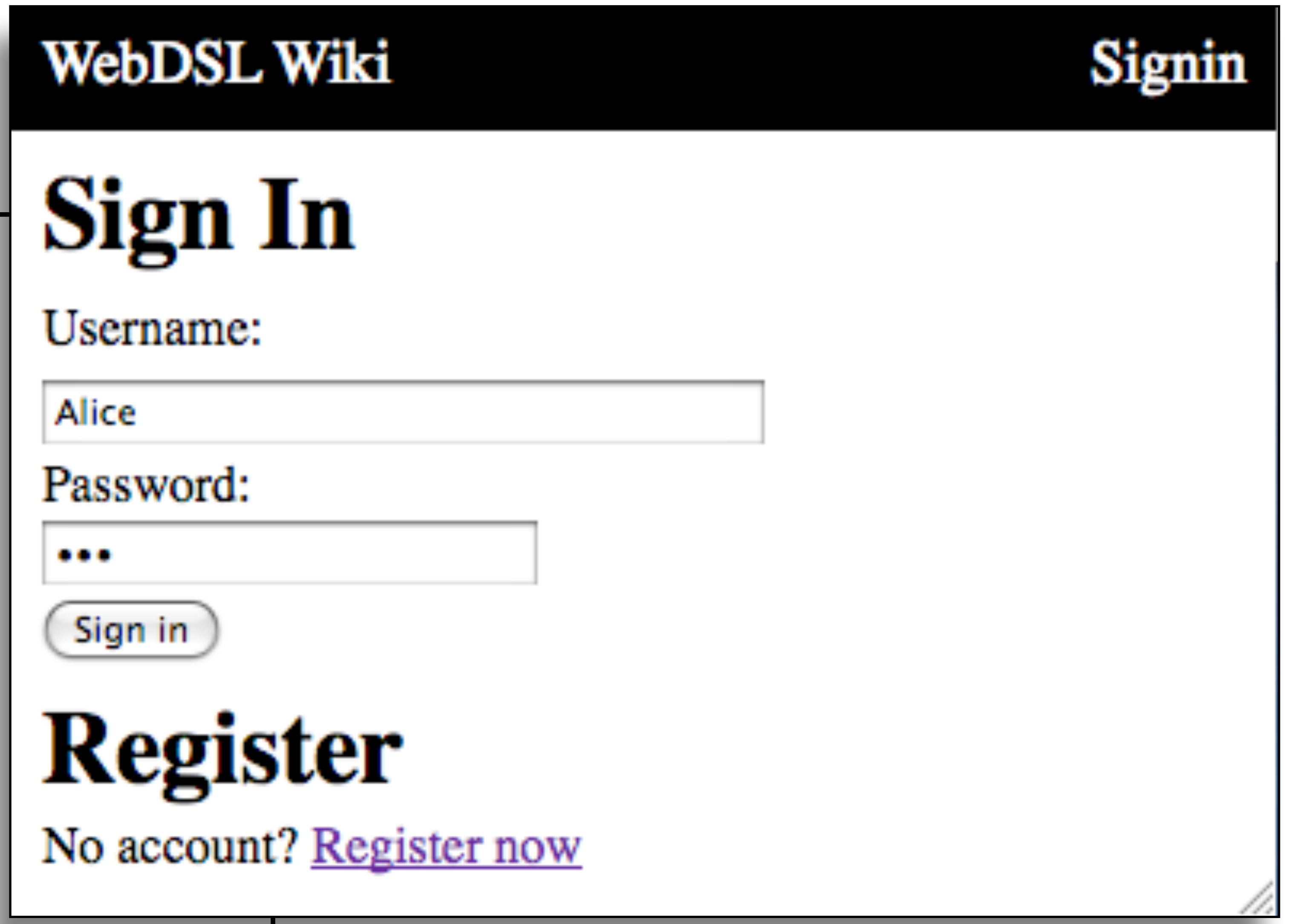
representation of principal

turn on access control

```
session securityContext {
  principal -> User
}
```

WebDSL: Authentication

```
define page signin() {
  var username : String
  var password : Secret
  action doit(){ signin(username, password); }
  main{
    header{"Sign In"}
    form{
      par{ label("Username: "){ input(username) } }
      par{ label("Password: "){ input(password) } }
      par{ action("Sign in", doit()) }
    }
    section{
      header{"Register"}
      par{ "No account? " navigate(register()){ "Register now" } }
    }
  }
}
```



WebDSL: Access Control Rules

```
access control rules

rule template *(*) { true }

rule page page(n : String) {
  loggedIn() || findPage(n) != null
}

rule page editpage(p : Page) {
  loggedIn()
}
```

‘anyone can view existing pages, only logged in users can create pages’

‘only logged in users may edit pages’

WebDSL: Linguistic Integration

Data models

- automatic persistence

User interface templates

- parameterized definition of page fragments
- request and response handling

Data validation

- form validation & data integrity

Access control rules and policies

- through constraints over objects

IceDust: Computing with Derived Values

Domain

- Information systems
- Data modelling with derived values

Design

- Native multiplicities and relations
- Different strategies for (re-)computing derived values
  - On demand (on read), incremental (on write), eventual (eventually consistent)

Implementation

- Generate WebDSL code
- Strategy implementation based on static dependency analysis

Applications

- WebLab grading logic

IceDust: Grading Logic

```
entity Submission {
  pass     : Boolean = grade >= 5.5 <+ false
  grade    : Float?  = if(conj(children.pass))
                         avg(children.grade)
}

entity Assignment {
  avgGrade : Float?  = avg(submissions.grade)
}

relation Assignment.parent     ? <-> * Assignment.children
relation Submission.assignment 1 <-> * Assignment.submissions
relation Submission.parent     ? <-> * Submission.children
```

IceDust: Grading Logic

```
gradeWeighted: Float = if(weightCustom > 0.0) totalGrade / weightCustom <+ 0.0 else totalGrade (inline)
gradeRounded : Float = max(gradeWeighted - (sub.penalty <+ 0.0) ++ 1.0).round1()              (inline)

gradeOnTime  : Float = if(sub.onTime <+ false) gradeRounded else 0.0                          (inline)

maxNotPassed : Float = max(0.0 ++ assignment.minimumToPass - 0.5).round1()                    (inline)
passSub      : Boolean = sub.filter(:AssignmentCollectionSubmission).passSub <+ true          (inline)
maxNotPass   : Float = if(passSub) gradeOnTime else min(gradeOnTime ++ maxNotPassed)          (inline)

grade        : Float = min(maxNotPass ++ scheme.maxGrade)                                   (eventual)
```

PixieDust

Domain

- Client-side web programming

Design

- Web views as IceDust-style derived values
- Incremental update of view based on changes in model

Implementation

- Generate JavaScript code
- Strategy implementation based on static dependency analysis

Applications

- Small toy application(s)

PixieDust: Model & View

```
model
  entity TodoList {
    todos : Todo* (inverse = Todo.list)
  }
  entity Todo {
    description : String
    finished    : Boolean
  }

view
  TodoList.view = div { ul { todos.itemView } }

  Todo.itemView = li {
    input[type="checkbox", value=finished]
    span { description }
  }
```

```
view
  TodoList {
    input : String = (init = ""   )
    show  : String = (init = "All")

    finishedTodos : Todo* =
      todos.filter(todo => todo.finished)
      (inverse = Todo.inverseFinishedTodos?)

    visibleTodos : Todo* =
      switch {
        case show == "All"      => todos
        case show == "Finished" => finishedTodos
        default => todos \ finishedTodos
      }
      (inverse = Todo.inverseVisibleTodos?)
  }
```

```
view
  TodoList {
    view : View = div {
      header
      ul { visibleTodos.itemView }
      footer
    }

    header : View = div {
      h1 { "Todos" }
      input[type="checkbox", value = allFinished,
                             onClick = toggleAll]
      StringInput[onClick = addTodo](input)
    }

    footer : View = div {
      todosLeft "items left"
      ul{
        visibilityButton(this, "All")
        visibilityButton(this, "Finished")
        visibilityButton(this, "Not finished")
      }
      if(count(finishedTodos) > 0)
        button[onClick = clearFinished]
    }
  }
  Todo {
    itemView : View = li { div {
      BooleanInput(finished)
      span { task }
      button[onClick=deleteTodo] { "X" }
    }}
  }
```

Research Challenges in Compiler Construction

Vision: Language Designer's Workbench

High-Level Declarative Language Definition

- Human readable / understandable definition
- Serves as reference documentation

Verification

- Automatically verify properties of language definition
- Type soundness of interpretation
- Type preservation of transformations
- Semantics preservation of transformation

Implementation

- Generate production quality tools from language definition
- Interpreter, compiler, IDE with refactoring, completion, …
- Correct-by-construction, high performance

Syntax

High-Performance Parsing

- JSGLR2: 2x to 10x speed-up compared to JSGLR
- More speed-up possible?
- Explore effects of different parse table formats (LR, SLR, LALR)

Error Recovery & Error Messages

- Apply error recovery approach of [TOPLAS12] to JSGLR2
- Generate high quality error messages

Incremental Parsing

- Re-parse effort proportional to change of program text
- Approach: adapt Graham/Wagner algorithm to SGLR

Extensible Syntax

- Extend syntax during parsing to support extensible languages

Workbench / Editor Services

Code Completion

- Semantic code completion based on static semantics

Refactoring

- Sound refactoring scripts
- Refactoring based on scope graph program model
- New NWO MasCot project: programming and validating software restructurings

Live Language Development

- Immediate response after edit of language definition
- Requires: incremental evaluation of all compiler components
- Ongoing work: PIE DSL for interactive software development pipelines

Language Deployment

- Generate stand-alone language implementation: PIE partial evaluation

Workbench / Editor Services

Portable Editors

- Portable editor bindings based on AESI model (Pelsmaeker)
- Case study: bindings for Visual Studio, IntelliJ, LSP

Web Editors

- Generate language-specific editors for use in web browser
- Architectural questions
    - All processing client-side? Stateful back-end on server? Scalability?
    - Performance of Web Assembly (WASM) better than JS?
- Collaborative editing (operational transform)

Interactive Notebooks

- Combine documents with code in several languages and results of execution

Statics with Statix

Specification of type systems with Statix

- Subset of CHR (Constraint Handling Rules) + domain-specific constraints for scope graphs and relations
- Support more advanced type systems
- Structural types, polymorphism (generics), sub-typing [OOPSLA'18]
  - Better encoding?
  - Generalization (for parametric polymorphism)?

Solver

- Matrix-based name resolution algorithm?
- Correctness wrt resolution calculus?
- Scalability: modular and incremental analysis?

Exploring Type System Design Landscape

Substructural Type Systems

- Linear types
- Rust

Gradual Type Systems

- Gradual type theory: encode calculi and experiment
- Implement existing gradual type checkers
  - Python, TypeScript, Dart, Hack
- Design gradual type system for Stratego

Dependent Types

- Agda, Idris

Syntax + Statics

Program Model

- Extend term data model to incorporate scopes and types
- Persistent storage
- Query: retrieve information based on scope graph model
  - All methods in class A
- Construction
  - well-formed wrt static semantics

Random Program Generation

- Generation of well-formed and well-typed programs
- based on syntax + static semantics
- for testing compilers and other language processing tools

Theme: Incremental Compilation

Make all (meta) language processing incremental

- Effort proportional to size of change

Modular analysis out of the box

- Static analysis incremental based on (scope graph) dependencies

Compiler = build system

- Use PIE to glue together language processing pipelines

In progress

- Incremental parsing
- Incremental compilation for Stratego (in Beta)
- Incremental compilation for WebDSL

Theme: Error Localization and Diagnosis

Error Localization

- What program element is responsible for the failure?
- Minimal unsatisfiable core
  - What is the smallest set of constraints that correspond to failure?

Error Diagnosis

- Generate good (understandable) explanation of error
- Based on unsat core

Studying Programming Languages

Courses

Compiler Construction B (Q2)

- Study back-end components of compiler

Software Verification (Q3)

- Learn the basics of mechanised verification with Agda dependently typed programming language

Web Programming Languages (Q3)

Language-Based Software Security (Q4)

Language Engineering Project (Q4)

- Develop a Spoofax language definition for an interesting language

Seminar Programming Languages (Q1)

- Read and discuss papers from the PL literature

System Validation (Q1)

- Check properties of (concurrent) software with model checking

Master Thesis Project in PL group

Industrial Internships

Oracle Labs (Zürich)

- Applications of Spoofax: GreenMarl, PGQL
- Other projects (Truffle/Graal)

Canon (Venlo)

- Designs and manufactures digital printers
- New project to investigate design of DSLs in digital printing domain

Philips (Best)

- Software restructuring

Other

- Opportunities for language design and implementation projects at other companies

Conferences

ACM Special Interest Group on Programming Languages

- http://sigplan.org/

Key SIGPLAN Conferences

- POPL: Principles of Programming Languages
- PLDI: Programming Language Design and Implementation
- ICFP: International Conference on Functional Programming
- OOPSLA/SPLASH: Systems, Programming Languages, and Applications
- SLE: Software Language Engineering
- GPCE: Generative Programming

Other Conferences

- ECOOP: European PL conference
- ESOP: European Symposium on Programming

Summer Schools

PLMW: Programming Languages Mentoring Workshop

- technical sessions on cutting-edge research in programming languages, and mentoring sessions on how to prepare for a research career
- At ICFP, POPL, PLDI, SPLASH

OPLSS: Oregon Programming Languages Summer School

- Foundational work on semantics and type theory
- Adanced program verification techniques
- Experience with applying the theory

DSSS: DeepSpec Summer School

- Formal verification

PLISS: Programming Language Implementation Summer School

- Programming language systems, implementation, analysis

After the Master

PhD

- Dive into PL research for four years
- Develop new PL theory, designs, and implementations
- Write research papers and a dissertation
- ~~Present your work at conferences around the world?~~

PL in industry

- Develop compilers, analyses, run-time systems
- Contribute to development of industrial programming languages
  - Oracle Labs (PGX), Google (Dart), Amazon (Cloud9), Canon (OIL)

Wanted: PhD Students in PL

Software Restructuring

- A principled approach to programming refactorings/restructurings
- Application: Transforming C++ code

Language Engineering

- Static semantics and type checking
- Deriving interpreters, compilers from dynamic semantics

Dependently Typed Programming

- Contributing to the semantics and implementation of Agda

Concurrency

Category Theory

Wanted: Grammar Engineer

Goal

- A collection of high quality syntax definitions for key languages
- Spoofax with `batteries included'
- Speeding up research case studies

Developing Syntax Definitions

- High quality
- High coverage

Research Assistant

- 4 - 8 hours per week (flexible)
- Appointment per project (language)

Wanted: Web Programmer

Academic Workflow Engineering

- Make university work better with web apps that automate workflows
- Education
  - WebLab, mystudyplanning, EvaTool
- Research
  - conf.researchr.org, researchr.org, mentoring
- Administration

Combine with PL research

- Use high-level web PLs (WebDSL, IceDust)
- Contribute to better abstractions for web programming

Exam

Exam and Resit

October 28: Exam

- 13:30-16:30

January 21: Resit

- 13:30-16:30

Topics

- Everything we studied in the lectures
- Example exam questions
  - homework assignments
  - exam from last year