Lecture 17: Beyond Compiler Construction

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CS4200 Compiler Construction
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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

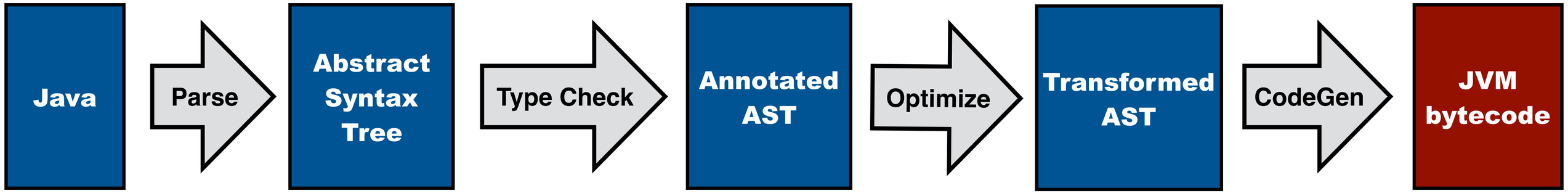
- Including topics for master thesis projects

Exam Dates

Compiler Components

What is a Compiler?

A bunch of components for translating programs



Compiler Construction = Building Variants of Java?

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)

Mini-Java Compiler

Syntax definition

- Parser through generation, design of abstract syntax

Desugaring

- Simple rewrite rules and strategies

Name analysis

- Lexical scoping
- Type-dependent name resolution

Type checking

- Class-based object-oriented language with sub-typing

Code generation

- Generation of Java Bytecode instructions using Jasmin assembly language
- AST-to-AST transformation

Further Study

More Compiler Components

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

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

Language design

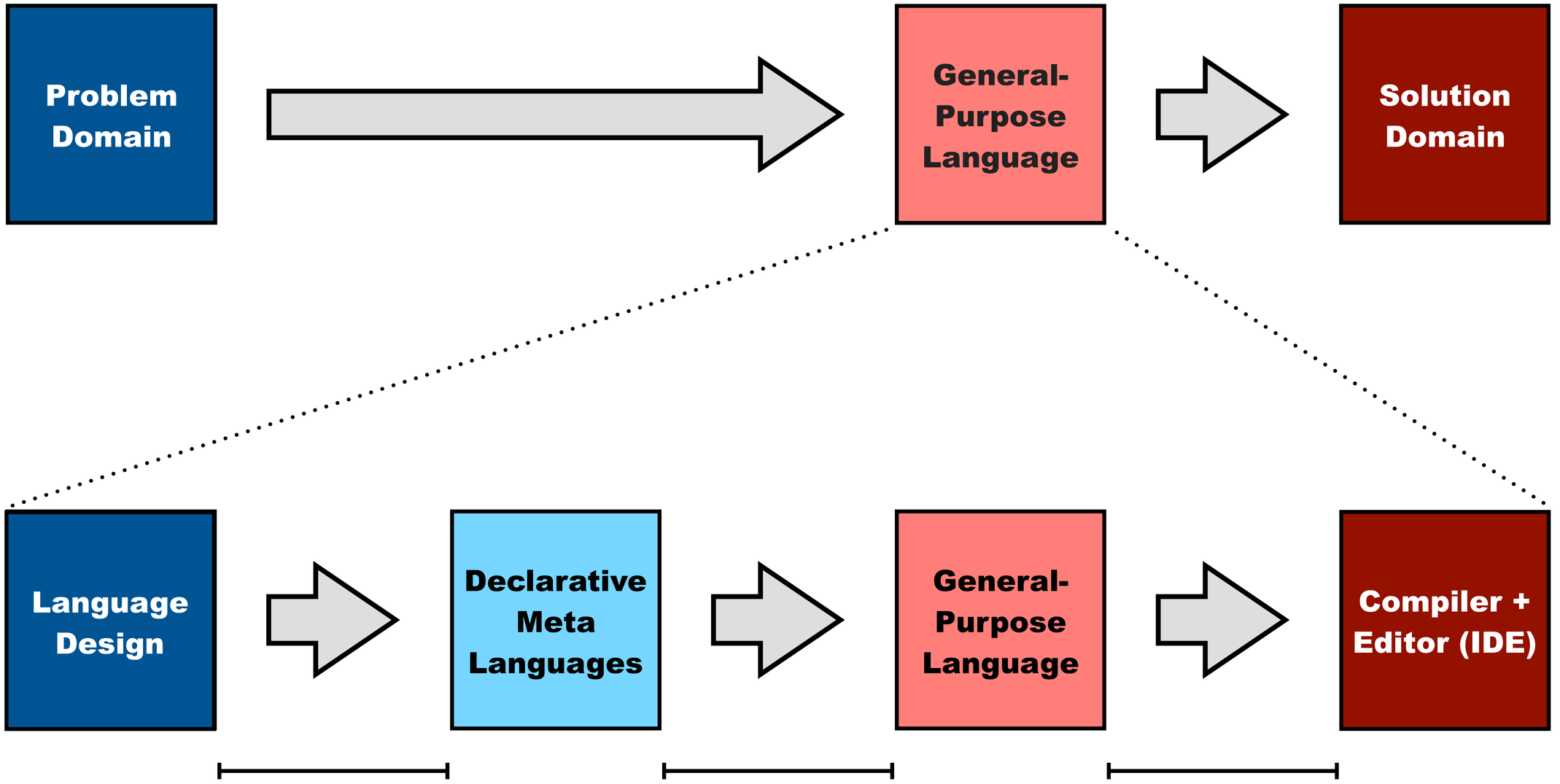
- Define the properties of a language
- Done by a language designer

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, …

NaBL2: 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

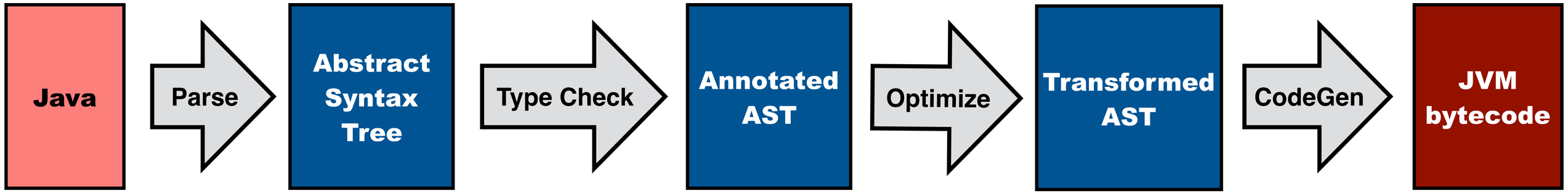
Compiler construction is a lot of fun …

… but when would I ever implement a programming language?

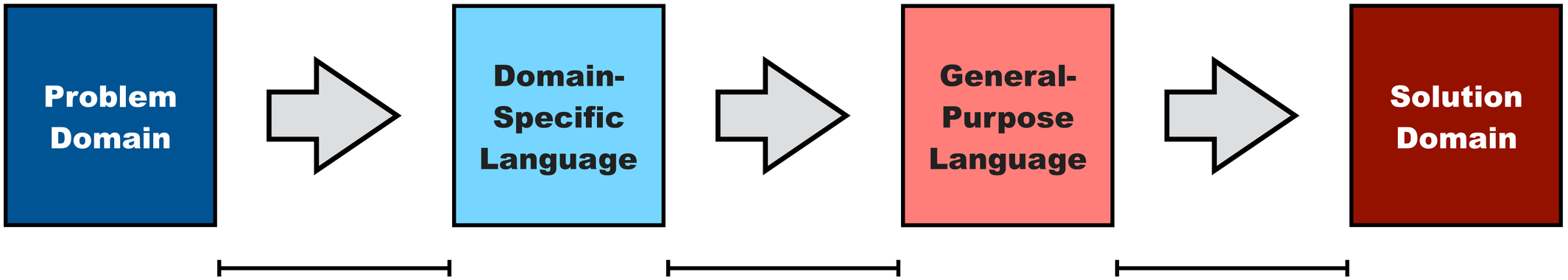
Domain-Specific Languages

Traditional Compiler

Source: high-level machine language



Target: low-level machine language



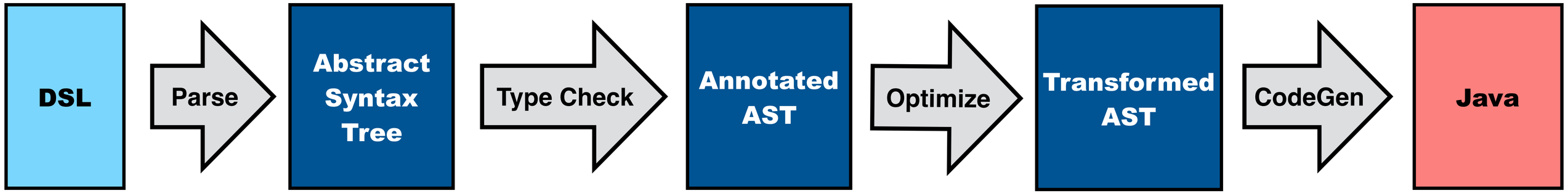
Domain-specific language (DSL)

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

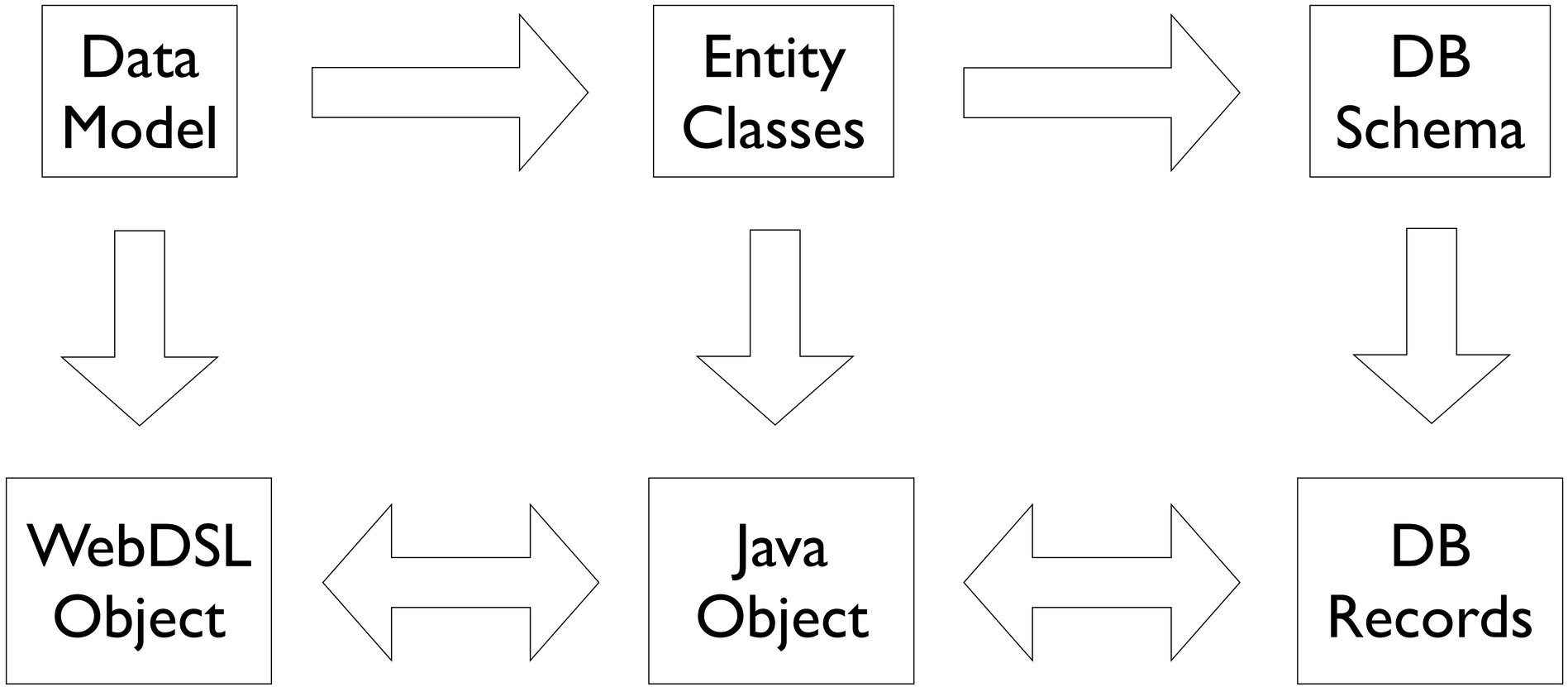
Implementation

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

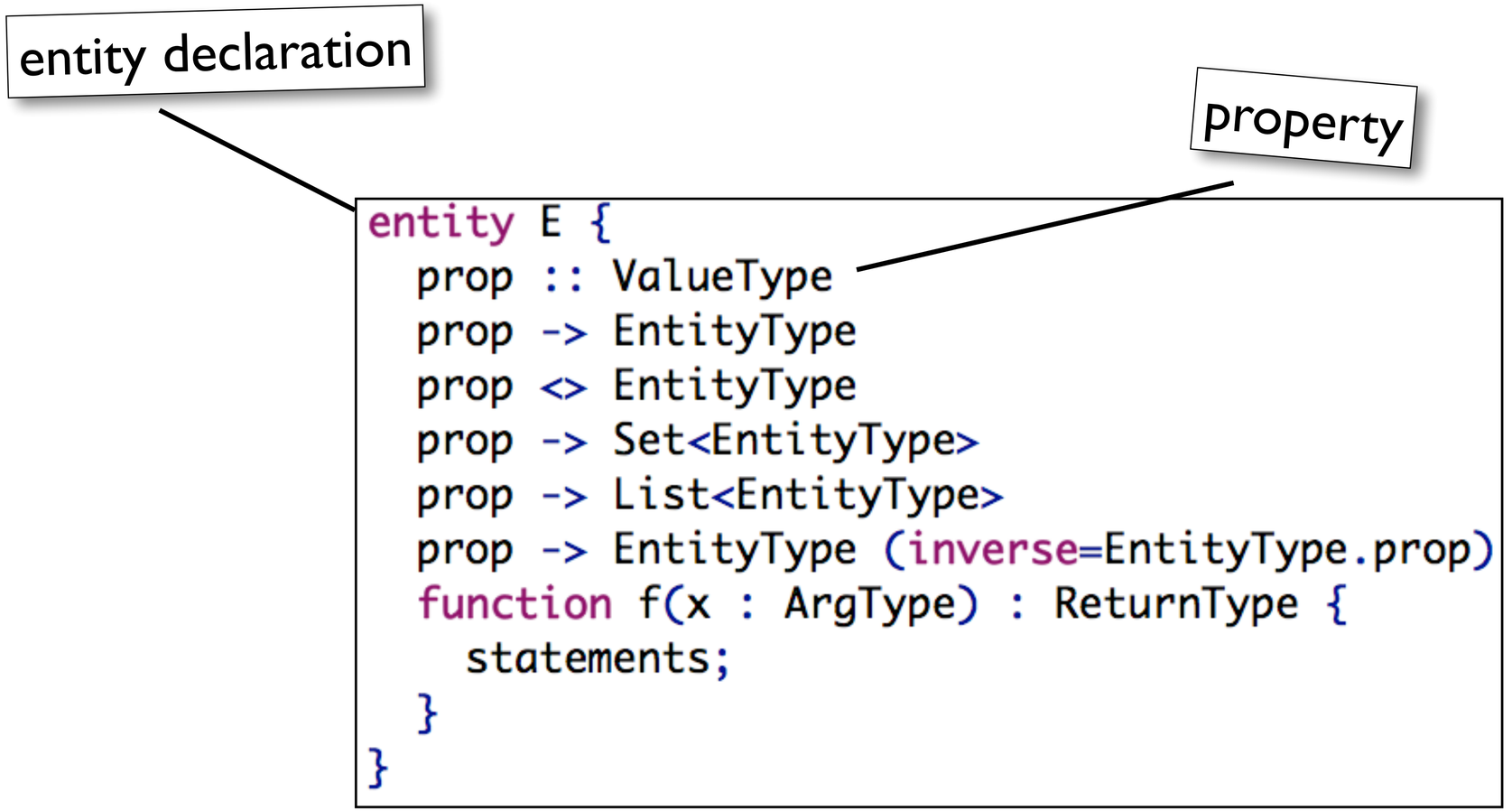
Applications

- WebLab, researchr.org, conf.researchr.org, EvaTool, mystudyplanning, …

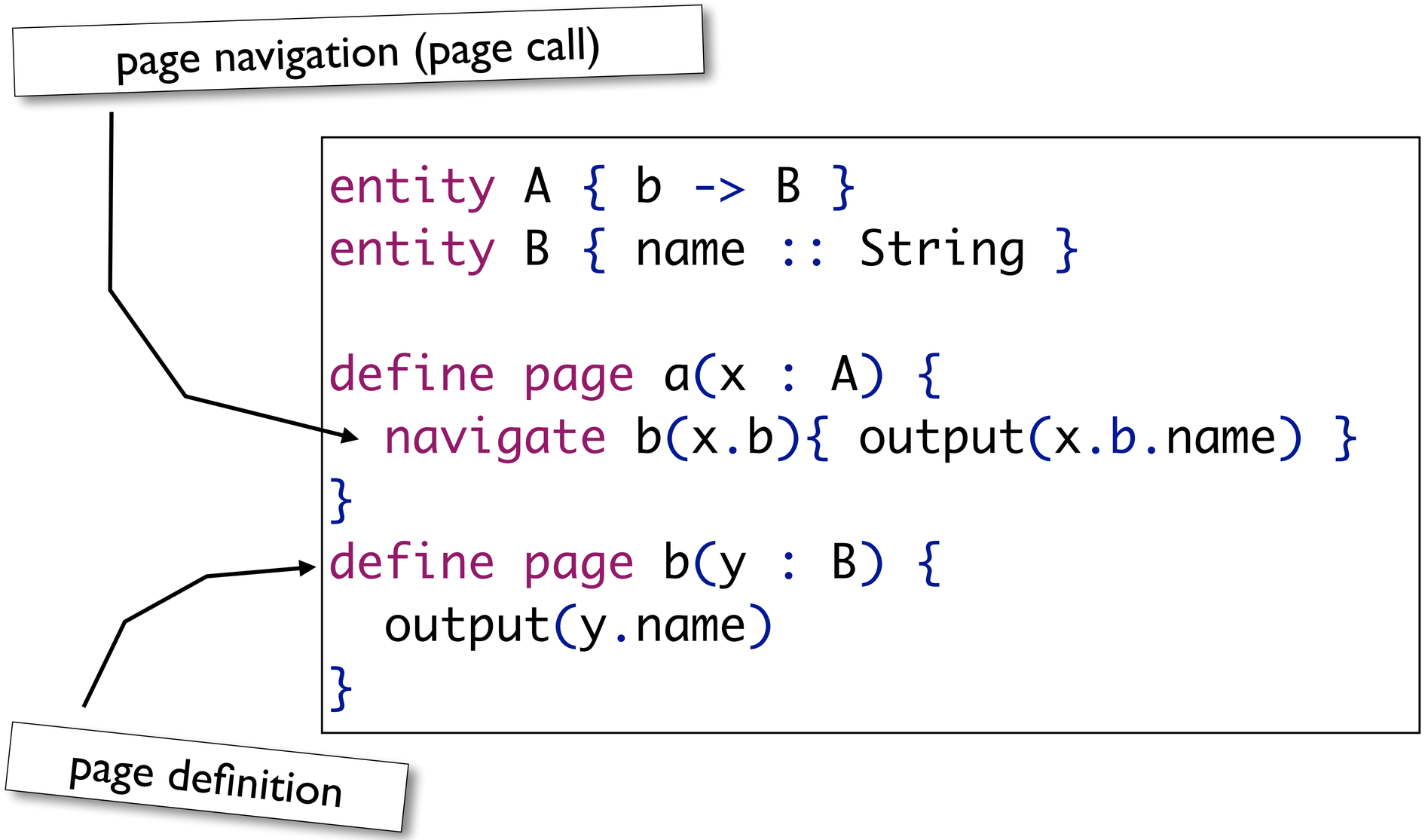
WebDSL: Automatic Persistence



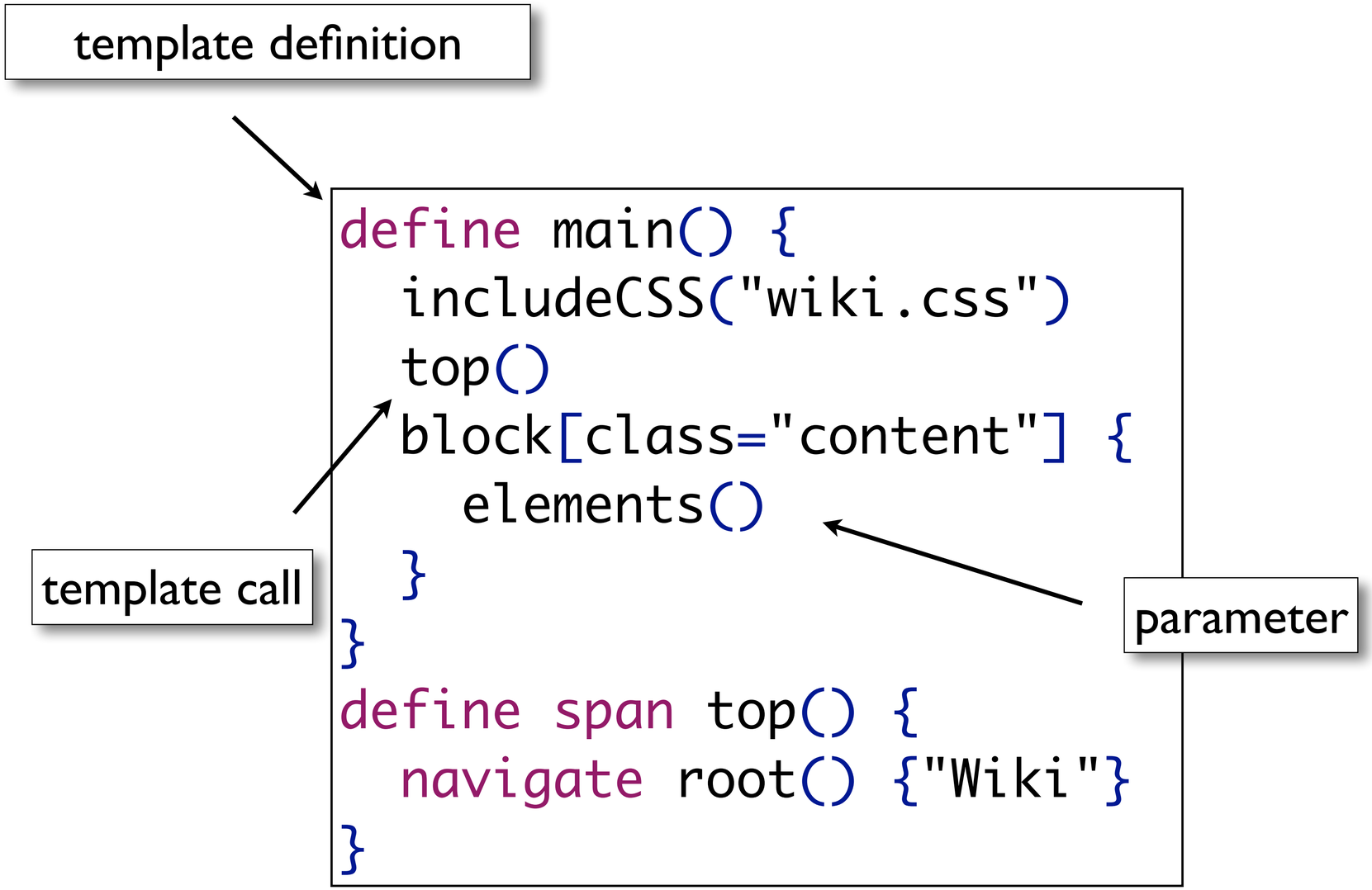
WebDSL: Entity Declarations



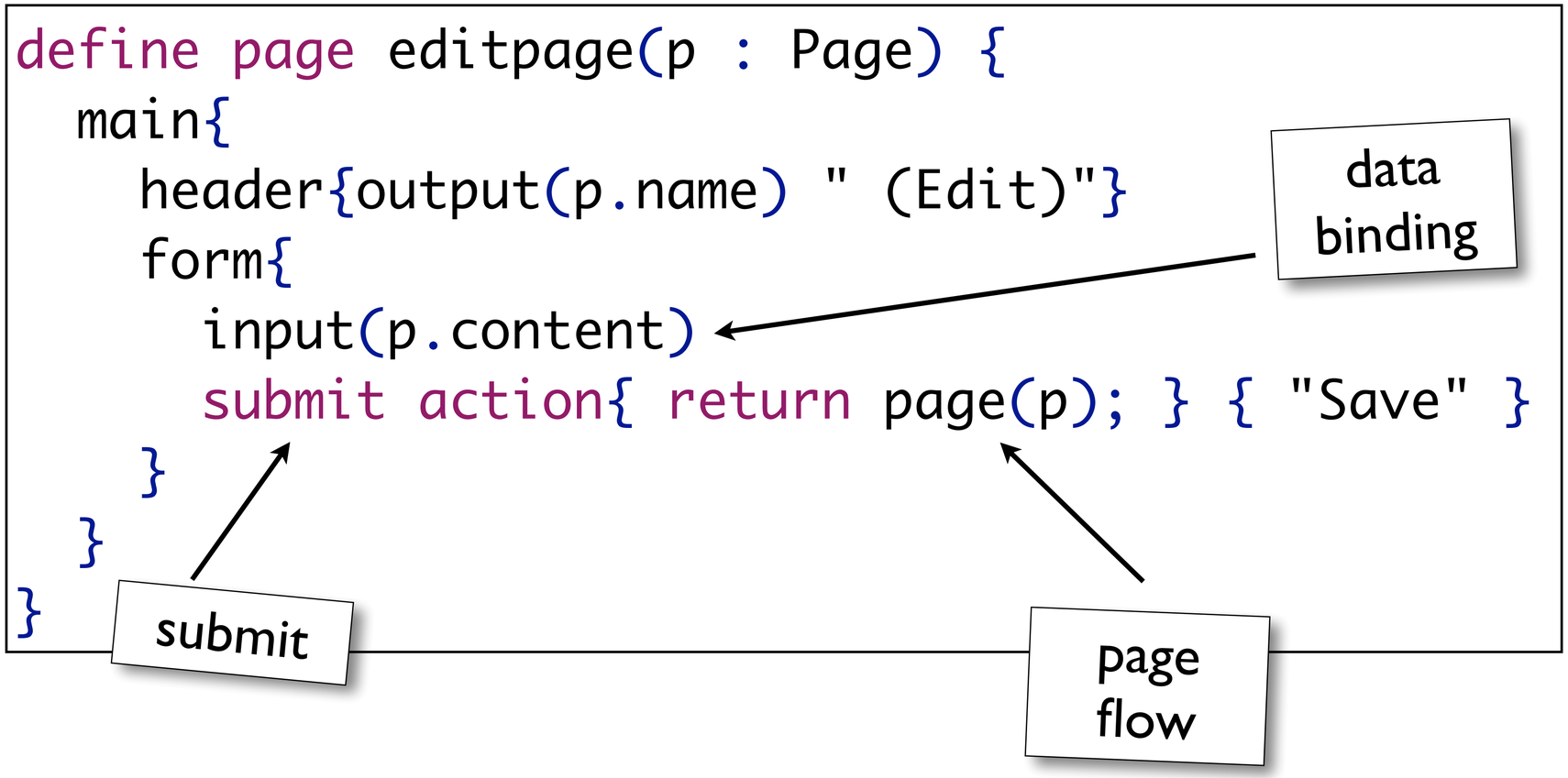
WebDSL: Page Definition & Navigation



WebDSL: Templates (Page Fragments)



WebDSL: Forms



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

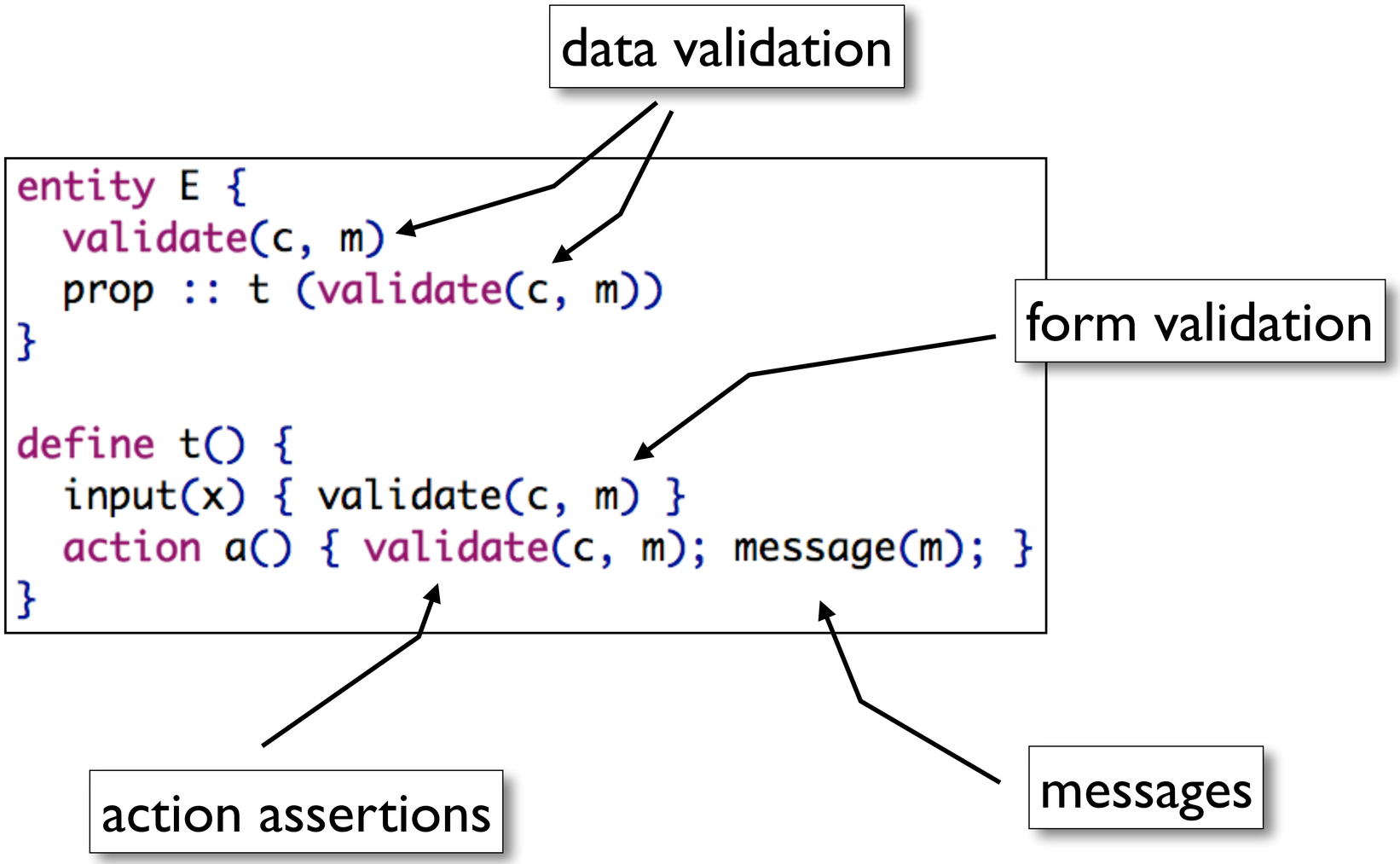
WebDSL: Search

search annotations

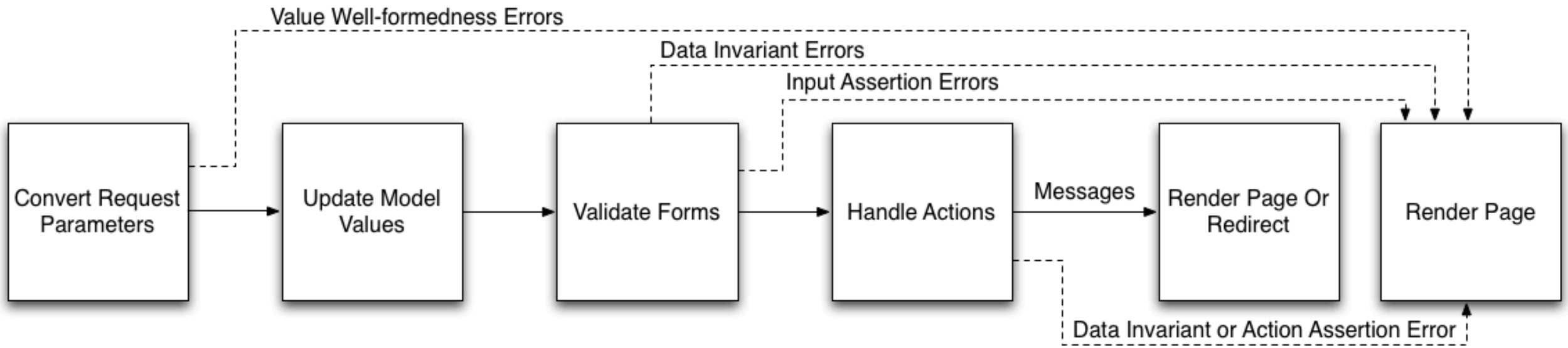
```
entity Page {
  name          :: String (id,searchable)
  content       :: WikiText (searchable)
  modified      :: DateTime
  authorSearch :: String (searchable) := authorNames()
}

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

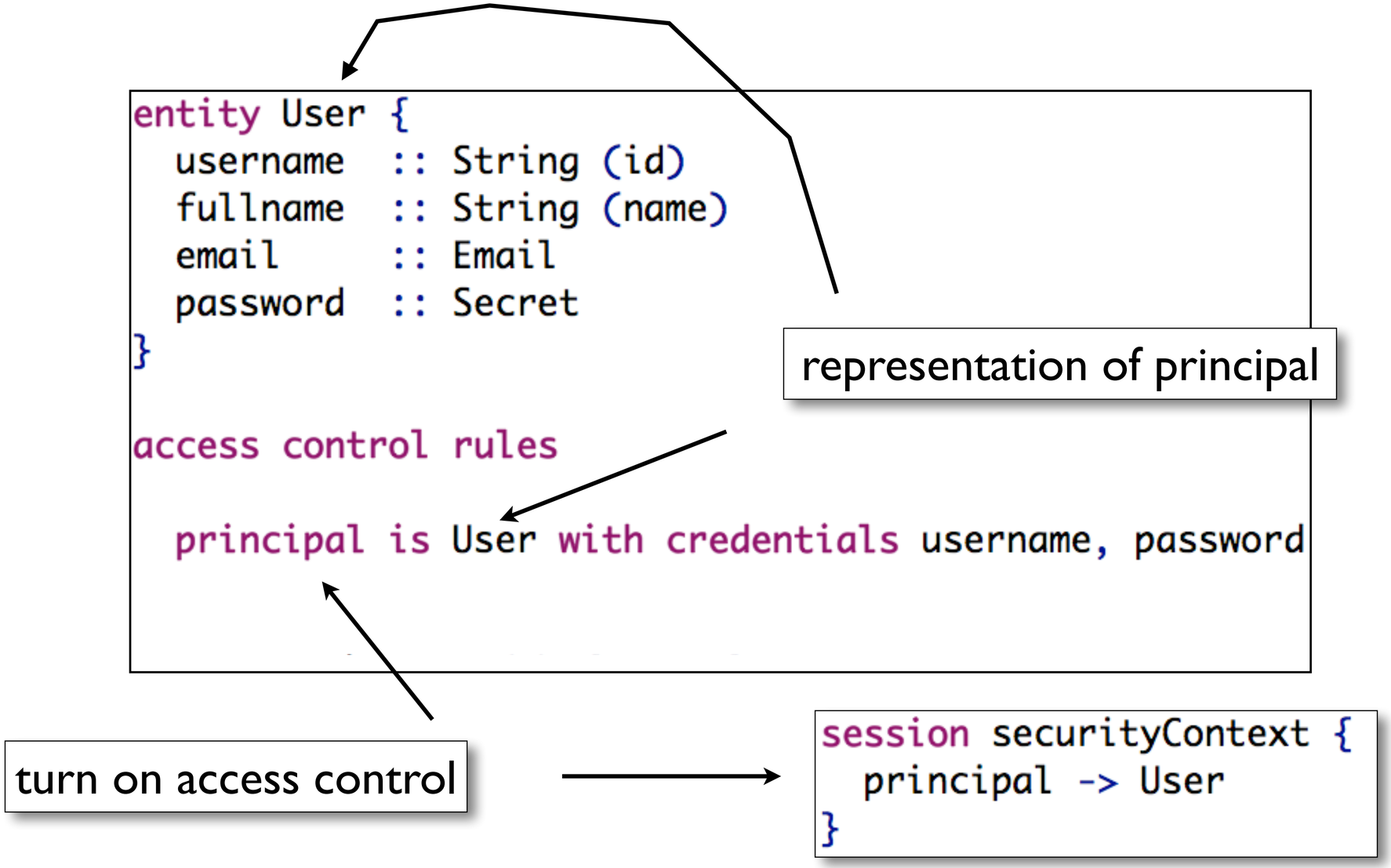
WebDSL: Validation Rules



WebDSL: Data Validation Lifecycle



WebDSL: securityContext



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 modeling 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

```
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" }
    }}
  }
```

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))
} }
```

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

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 and IntelliJ

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

Specification of type systems

- Statix: NaBL2 successor
- Support more advanced type systems
- Structural types, polymorphism (generics), sub-typing
- Subset of CHR (Constraint Handling Rules) + domain-specific constraints for scope graphs and relations

Solver

- Matrix-based name resolution algorithm
- Correctness wrt resolution calculus?
- Scalability: Incremental analysis?

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 programs based on syntax + static semantics for testing

Transformation

New Transformation Language

- Operating on richer program model
- Generic (traversal) strategies
- Statically typed
- Type-preserving transformations
  - intrinsically or extrinsically verified?
- Semantics-preserving transformations
  - intrinsically or extrinsically verified?

Transformation Algorithms

- Refactorings, Optimizations

Code Generation / Instruction Selection

- BURS: Bottom-up rewrite system: Find cheapest / best mapping to code

Analysis

FlowSpec

- Declarative specification of data-flow analyses
- Increase expressiveness to cover more analyses
- High-performance execution of analyses
- Incremental execution of analyses (during transformation)

Data-flow Dependent Static Semantics

- Definite assignment in Java
- Borrow checking in Rust

Dynamics

Interpreters from dynamic semantic specification

- Prototype for DynSem [RTA15] applied to Grace [DLS17], Tiger

Frame-based interpreters

- Scope graph describes memory model [ECOOP16]
- Define in DynSem applied to realistic languages
- Correct-by-construction [POPL18] => dependently-typed DynSem
- Language-independent garbage collection

Partial evaluation

- Specialize DynSem interpreter to language-specific set of semantic rules
- Specialize language-specific rules to specific program

Compiler generation

- Derive compiler from dynamic semantics specification

Verification

Intrinsically Typed Definitional Interpreters

- For Middle Weight Java (MJ) in Agda [POPL18]
- Extend to more sophisticated type systems (generics, System F)
- Extend to more sophisticated effect systems (continutations, algebraic effects)
- Extend approach to other operations: transformation, code generation

Extrinsic Proofs

- Generation of extrinsic type soundness proof
- Other properties

Other Verification Challenges

- Semantics preservation of DSL code generators
- Correctness of meta-DSLs

Studying Programming Languages

Courses

Dynamic and Static Analysis for Software Security (Q2)

- See title

Software Verification (Q3/Q4?)

- Learn the basics of mechanised verification with Coq proof assistant

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 (esp. Zürich)

- Applications of Spoofax: GreenMarl, PGQL
- Other projects

Océ (Venlo)

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

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 OO conference; in Amsterdam July 2018
- Curry On 2018

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

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 (GreenMarl), Google (Dart), Amazon (Cloud9)

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
- Administration

Combine with PL research

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

Exam

Exams and Resits

January 29: Exam Q2

- 18:30-21:30
- Topics of Q2 + type checking/constraints

February 14: Resit Q1

- 13:30-16:30

April 12: Resit Q2

- 13:30-16:30