Teaching Programming with the Kernel Language Approach

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Overview

- Programming needs both technology and science
  - Current approaches to teach programming are lacking
- Example: concurrent programming
  - Monitors in Java
  - The broad view
- The kernel language approach
  - A family of kernel languages
  - Formal semantics for the practicing programmer
  - Creative extension principle
- Teaching experience
  - Textbook and software
  - Courses taught
  - Curriculum recommendations
- Conclusions

What is programming?

- We define **programming** broadly as the step from specification to running program, which consists in designing the architecture and its abstractions and coding them into a programming language
- Doing programming well requires understanding two topics:
  - A **technology**: a set of practical techniques, tools, and standards
  - A **science**: a scientific theory that explains the technology
- Teaching programming well therefore requires teaching both the technology and the science
  - Surprisingly, programming is almost never taught in this way. It is almost always taught as a **craft** in the context of current technology (e.g., Java and its tools). If there is any science, it is either limited to the tools or too theoretical.
- We propose a remedy, **the kernel language approach**

Concurrent programming: monitors in Java

- Concurrent programming with shared state and monitors (as done in Java) is **so complicated** that it is taught only in advanced courses (upper level undergraduate)
- The implementation of concurrency in Java is **expensive**
- Java-taught programmers therefore reach the conclusion that concurrency is ***always* complicated and expensive**
- But this is **completely false**: there are useful forms of concurrency (e.g., dataflow, streams, active objects) that are easy to use and can be implemented efficiently
- Therefore programmers should be taught about concurrency in a broader way

Concurrent programming: the broad view

- We distinguish four forms of practical concurrent programming (in order of increasing difficulty):
  - **Sequential programming + variants**
  - **Declarative concurrency (lazy and eager):** add threads to a functional language and use **dataflow** to decouple independent calculations
  - **Message passing between active objects:** Erlang style, each thread runs a functional program, threads communicate through asynchronous channels
  - **Atomic actions on shared state:** Java style, using monitors and transactions
- The Java style is the most popular, yet it is the most difficult to program
- **Declarative concurrency** especially is quite useful, yet is not widely known
  - Programming with streams and dataflow
  - All the programming and reasoning techniques of sequential declarative programming apply (concurrent programs give the same results as sequential ones)
  - Deep characterization: lack of observable nondeterminism

Approaches to teach programming

- As a craft
  - Most popular; single paradigm and language
- As a branch of mathematics
  - Usually too theoretical
  - Dijkstra has done this successfully, but with only a small language
- In terms of concepts
  - Start with simple concepts and gradually introduce more sophisticated ones, as they are needed
  - The concepts are not limited to single languages or paradigms
  - Abelson & Sussman and its successors use this approach

The kernel language approach

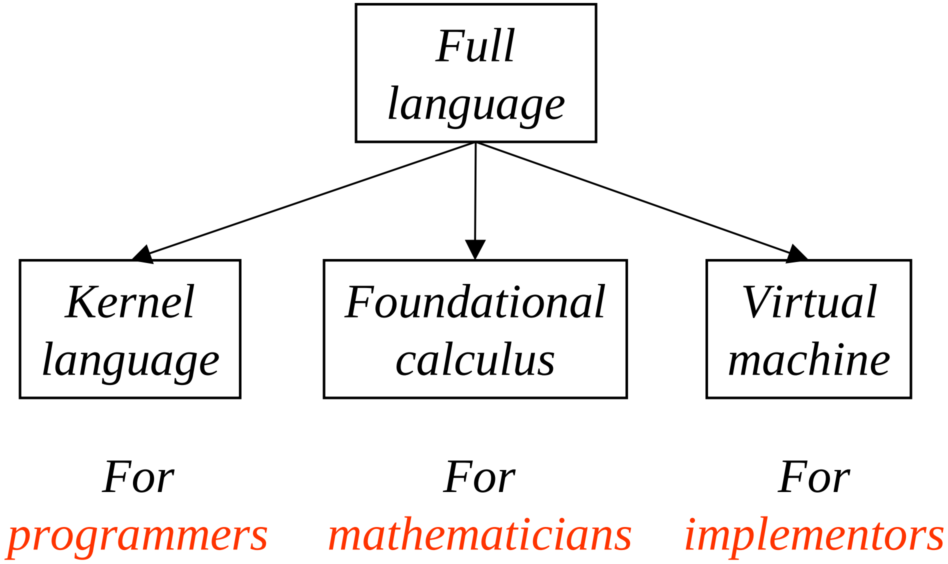
- How can we teach programming as a unified discipline?
  - There are too many languages
  - Teaching a few carefully-selected languages, say one per paradigm, does not solve the problem: it multiplies the effort of student and teacher but does not show the deep relationships between the paradigms
- A better approach would be based on concepts, not languages, as done by Abelson & Sussman
- We organize the concepts into simple languages called kernel languages
  - A wide variety of languages and programming paradigms can be translated into a small set of closely-related kernel languages
  - We give an operational semantics in terms of a simple abstract machine at a high level of abstraction
  - We try to be as comprehensive as possible, incorporating all of the most important concepts. In particular, we have a comprehensive treatment of concurrency.
  - We organize the concepts according to the creative extension principle

Related work

- By far the closest books are “Structure and Interpretation of Computer Programs”, by Abelson & Sussman, and its successor “Essentials of Programming Languages”, by Friedman et al.
  - Both these books and ours are based on concepts: they *“liberate programming from the tyranny of syntax” (Felleisen et al)*
- Our approach differs in four major ways:
  - Translation:
    - We translate into kernel languages instead of writing interpreters
  - Formal semantics:
    - We give a simple but precise abstract machine that allows reasoning about time and space complexity.
  - Breadth:
    - We go deeper into concurrency, capabilities, and logic programming. We apply the approach to user interfaces, distributed computing, and constraint programming. All concepts are fully implemented in the Mozart system.
  - Methodology:
    - We organize the concepts according to the creative extension principle, which indicates when new concepts are needed and gives a criterium for judging them

The kernel language approach (2)

- Kernel languages have a small number of programmer-significant elements
- Their purpose is to understand programming from the programmer's viewpoint
- They are given a semantics which allows the practicing programmer to reason about correctness and complexity at a high level of abstraction


Full language

Kernel language

Foundational calculus

Virtual machine

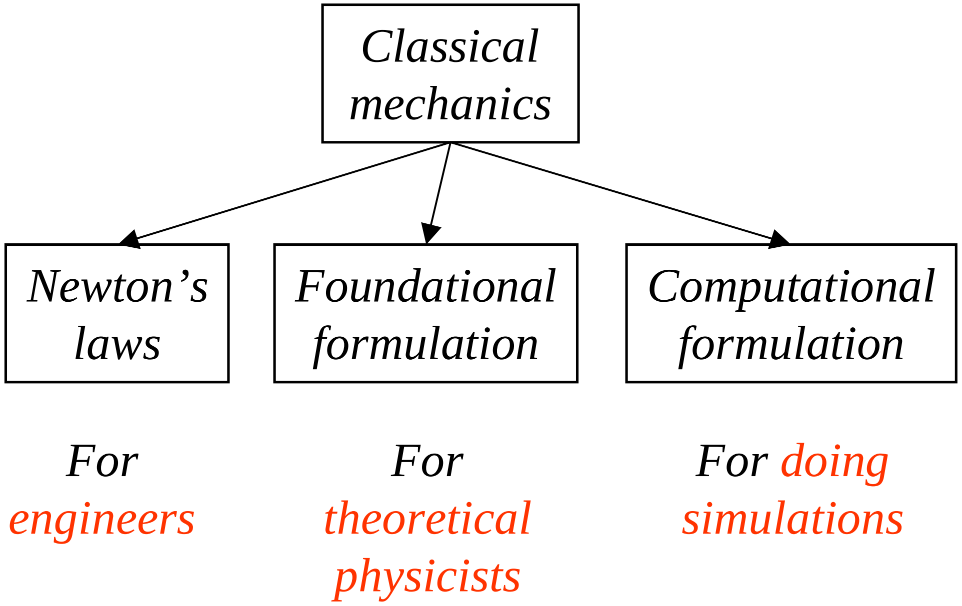
For programmers

For mathematicians

For implementors

The kernel language approach (3): analogy with classical mechanics

- Classical mechanics is a branch of physics that is widely used in engineering
- Classical mechanics is based on a small set of physical laws
- These laws can be formulated in three basically different ways, which are useful for different communities
- For engineers, the formulation based on Newton's laws (and its derivations) is the most useful in practice (back of envelope)



Classical mechanics

Newton's laws

Foundational formulation

Computational formulation

For engineers

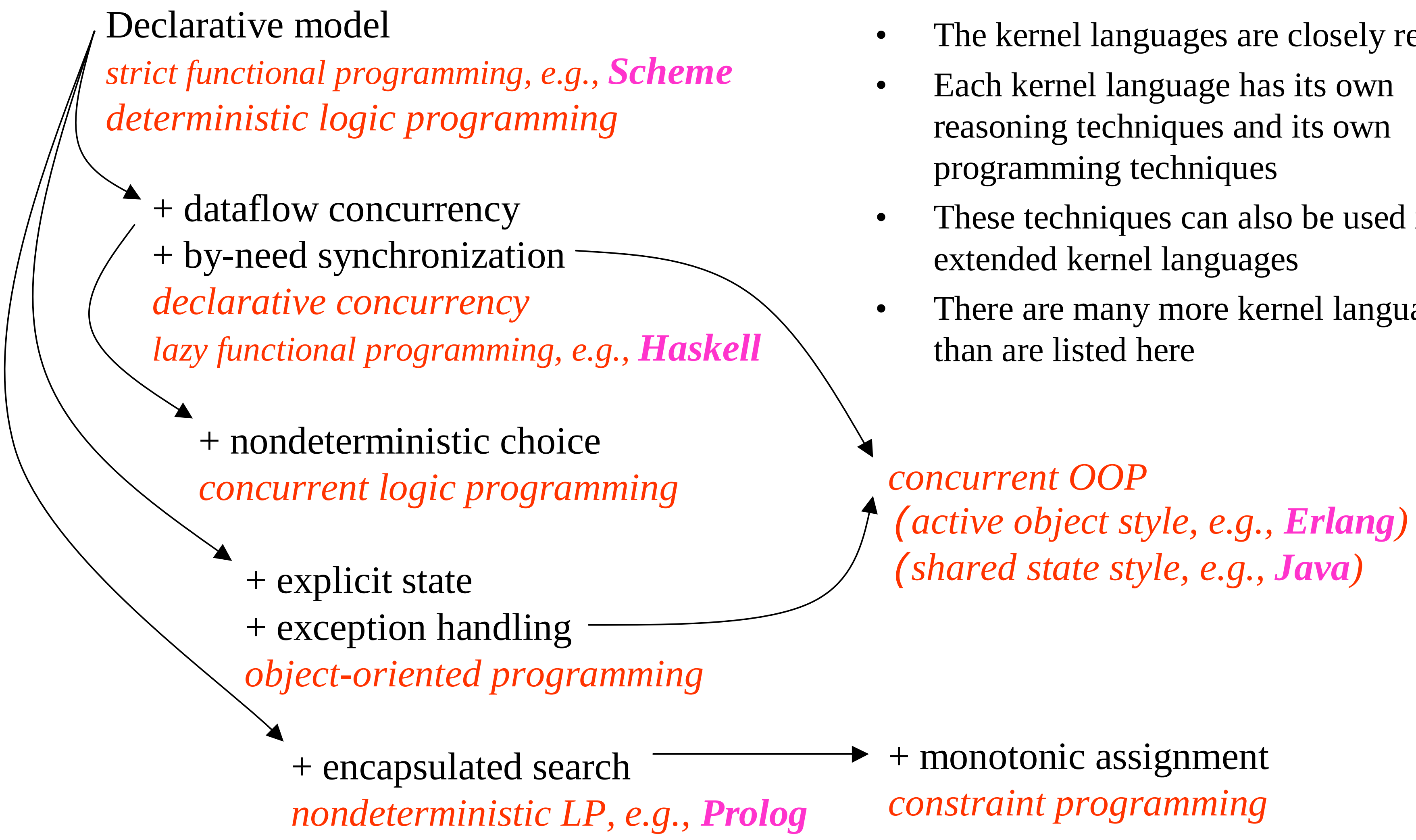
For theoretical physicists

For doing simulations

What concepts should be in the kernel languages?

- There are many possibilities
  - We propose a methodology to design kernel languages
  - The methodology underlies our textbook and pedagogy
- **Creative extension principle**
  - Start from a simple base language
  - Programming with this language exposes limitations in expressiveness
    - Programs become complex for reasons independent of the application
    - This means that there is a new concept waiting in the wings!
    - Examples: exceptions, capabilities, concurrency, laziness, search, state
  - There is always a choice:
    - To encode the concept in the language, which makes programs complicated but keeps the language semantics simple
    - To add the concept to the language. If the concept is chosen well, the program becomes simple and the language semantics is extended in a modular way.
      - *Can always program in the original subset to get original semantics back*
  - Iterating this process gives a family of kernel languages

A family of kernel languages



Declarative model

strict functional programming, e.g., ***Scheme***

deterministic logic programming

\+ dataflow concurrency

\+ by-need synchronization

declarative concurrency

lazy functional programming, e.g., ***Haskell***

\+ nondeterministic choice

concurrent logic programming

\+ explicit state

\+ exception handling

object-oriented programming

\+ encapsulated search

nondeterministic LP, e.g., ***Prolog***

concurrent OOP

(active object style, e.g., ***Erlang****)*

(shared state style, e.g., ***Java****)*

\+ monotonic assignment

constraint programming

- The kernel languages are closely related
- Each kernel language has its own reasoning techniques and its own programming techniques
- These techniques can also be used in extended kernel languages
- There are many more kernel languages than are listed here

Most general language (so far)

<s> ::=

skip	*Empty statement*
<s>$_1$ <s>$_2$	*Statement sequence*
local <x> **in** <s> **end**	*Variable creation*
<x>$_1$=<x>$_2$	*Variable-variable binding*
<x>=<v>	*Value creation*
{<x> <y>$_1$ … <y>$_n$}	*Procedure application*
if <x> **then** <s>$_1$ **else** <s>$_2$ **end**	*Conditional*
case <x> **of** <p> **then** <s>$_1$ **else** <s>$_2$ **end**	*Pattern matching*
thread <s> **end**	*Thread creation*
{ByNeed <x>$_1$ <x>$_2$}	*Trigger creation (laziness)*
(**choice** + **search** *)*	*Encapsulated search*
{NewName <x>}	*Name creation (security)*
try <s>$_1$ **catch** <x> **then** <s>$_2$ **end**	*Exception context*
raise <x> **end**	*Raise exception*
{NewCell <x>$_1$ <x>$_2$}	*Cell creation*
{Exchange <x>$_1$ <x>$_2$ <x>$_3$}	*Cell exchange*

Most general language (2)

- There are three kinds of values in the language: numbers, records, and procedures

<v> ::= <number> | <record> | <procedure>

<number> ::= <int> | <float>

<record>, <p> ::= <lit>(<feat>$_1$:<x>$_1$ … <feat>$_n$:<x>$_n$)

<procedure> ::= **proc** {$ <x>$_1$ … <x>$_n$} <s> **end**

<lit> ::= <atom> | <bool>
<feat> ::= <atom> | <bool> | <int>
<bool> ::= **true** | **false**

Formal semantics (1)

- We define a simple but precise abstract machine
  - Other semantics tie on to this (SOS, axiomatic, logical)
- Basic concepts:
  - A *single-assignment store* σ is a set of store variables $x_1, \ldots, x_k$, that are partitioned into sets of equal unbound variables and variables bound to a number, record, or procedure
  - An *environment* E is a mapping from variable identifiers to store variables, $\{\langle x\rangle_1 \rightarrow x_1, \ldots, \langle x\rangle_n \rightarrow x_n\}$
  - A *semantic statement* is a pair (<s>, E) where <s> is a statement and E is an environment
  - An *execution state* is a pair (ST, σ) where ST is a stack of semantic statements
  - A *computation* is a sequence of execution states starting from an initial state: $(ST_0, \sigma_0) \rightarrow (ST_1, \sigma_1) \rightarrow (ST_2, \sigma_2) \rightarrow \ldots$

Formal semantics (2)

- Program execution
  - The initial execution state is ([(<s>,ϕ)], ϕ). The initial semantic statement is (<s>,ϕ) with an empty environment, and the initial store is empty.
  - At each execution step, the first element of *ST* is popped and execution proceeds according to the form of the element
  - The final execution state (if it exists) is one in which the semantic stack is empty.
- A semantic stack can be in one of three run-time states:
  - *running*: *ST* can do an execution step
  - *terminated*: *ST* is empty
  - *suspended*: *ST* is not empty but cannot do a step

Example: the **local** statement

- The semantic statement is (**local** <x> **in** <s> **end**, *E*)
- Execution consists of the following actions:
  - Create a new variable *x* in the store
  - Push (<s>, $E+\{\text{<x>}\rightarrow x\}$) on the stack
- Students clearly see the difference between identifiers (bits of syntax, like <x>) and variables in memory (entities that take part in the computation, like *x*)

Example: the **if** statement

- The semantic statement is (**if** <x> **then** $<s>_1$ **else** $<s>_2$ **end**, *E*)
- This statement has an activation condition: *E*(<x>) must be determined, i.e., bound to a number, record, or procedure
- Execution consists of the following actions:
  - If the activation condition is **true**, then do the following actions:
    - If *E*(<x>) is not a boolean (**true** or **false**), then raise an error condition
    - If *E*(<x>) is **true**, then push ($<s>_1$, *E*) on the stack
    - If *E*(<x>) is **false**, then push ($<s>_2$, *E*) on the stack
  - If the activation condition is **false**, then execution suspends
- If some other activity in the system makes the activation condition true, then execution can continue. This does dataflow programming, which is at the heart of declarative concurrency.

Example: procedures

- A procedure value is a pair $(\textbf{proc}\ \{\$\ <y>_1 \ldots <y>_n\}\ <s>\ \textbf{end},\ CE)$ where CE (the « contextual environment ») is $E|_{\{<z>1,\ \ldots,\ <z>m\},}$ where E is the environment where the procedure is defined and $\{<z>_1, \ldots, <z>_m\}$ is the set of external identifiers of the procedure

- In a procedure call $(\{<x>\ <x>_1 \ldots <x>_n\},\ E)$:
  - if $E(<x>)$ has the form $(\textbf{proc}\ \{\$\ <y>_1 \ldots <y>_n\}\ <s>\ \textbf{end},\ CE)$, then
  - push $(<s>,\ CE + \{<y>_1 \rightarrow E(<x>_1), \ldots, <y>_n \rightarrow E(<x>_n)\})$

- This allows higher-order programming as in functional languages
  - A basic building block for abstraction, genericity, instantiation, and embedding, the techniques that underlie objects and components

Programming paradigms as epiphenomena

- The kernel approach lets us organize programming in three levels:
  - **Concepts**: compositionality, encapsulation, lexical scoping, higher-orderness, capability property, concurrency, dataflow, laziness, state, inheritance, ...
  - **Techniques**: how to write programs with these concepts
  - **Computation models** (« paradigms »): each model contains a fixed set of concepts and is realized with data entities, operations, and a language
- Programming paradigms *emerge in a natural way* when programming (as a kind of epiphenomenon), depending on which concepts one uses in a model and which properties hold of the resulting model
  - **Reasoning techniques** depend on paradigm. Paradigms with fewer concepts are less expressive but simplify reasoning.
- It is often advantageous for programs to use several paradigms together (examples: concurrency, user interfaces, …)

Teaching experience

- Materials
  - Textbook: "**Concepts, Techniques, and Models of Computer Programming**"
    - See: `http://www.info.ucl.ac.be/people/PVR/book.html`
    - Work in progress since early 2000; recently sent to publisher
  - Software: **Mozart Programming System**
    - See: `http://www.mozart-oz.org/`
    - Open source system used in many R&D projects; active development since 1991
    - Implements the Oz language (fits well the kernel language approach)
    - Developed by the Mozart Consortium (groups in Germany, Sweden, Belgium)
  - Transparencies, lab sessions, interactive demos
- Courses taught (at UCL, KTH, NMSU, Cairo University)
  - Audiences covered so far: second to fourth year CS majors, graduate CS majors, second-year engineering (both CS and non CS majors)
  - Course topics: introduction to programming, algorithmic programming concepts, semantics, concurrent programming, distributed computing, declarative programming
- Not intended as a first course
  - The approach could likely be adapted; we have not done this

Curriculum recommendations

- We propose the following division of the discipline of programming into three topics:
  - Concepts and techniques
  - Algorithms and data structures
  - Program design and software engineering
- We recommend teaching the first and third topics together, introducing concepts and design principles concurrently
  - Textbook treats topic 1 in depth and gives introductions to the others
- At UCL, each topic is given 8 semester-hours (lectures + lab sessions)
  - All three together take one full semester, spread out over the complete curriculum
  - The complete curriculum has three full years of CS topics supplemented with one or two full years of non-CS topics for the licentiate and engineering degrees respectively

Conclusions

- The kernel language approach focuses on concepts and programming techniques, not on programming languages or paradigms
- Practical languages are translated into simple kernel languages based on small sets of programmer-significant concepts
  - The kernel languages have much in common, which allows them to show clearly the deep relationships between different languages and programming paradigms
  - We give a semantics at the right level of abstraction for the practicing programmer, to allow reasoning about correctness and complexity
- We support the approach with a textbook, teaching materials, and a software platform
  - We are teaching with the textbook in four universities (F 2001, Sp 2002, …), from second-year to graduate courses
  - The textbook extends the concepts-first approach of Abelson & Sussman with formal semantics, wider coverage, and a justifiable choice of concepts
  - The software platform is high quality and runs all programs in the book
- Based on our experience, we give recommendations on how to teach programming in the CS curriculum