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Domain Analysis & Description

The Implicit and Explicit Semantics Problem

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The domain analysis & description calculi introduced in [26] is shown to alleviate the issue of implicit semantics [1, 2]. The claim is made that domain descriptions, whether informal, or as also here, formal, amount to an explicit semantics for what is otherwise implicit if not described! I claim that [26] provides an answer to the claim in both [1, 2] that “The contexts of the systems in these cases are treated as second-class citizens ...”, respectively “In general, modeling languages are not equipped with resources, concepts or entities handling explicitly domain engineering features and characteristics (domain knowledge) in which the modeled systems evolve”.

1 Introduction

1.1 On the Issues of Implicit and Explicit Semantics

In [1] the issues of implicit and explicit semantics are analysed. It appears, from [1], that when an issue of software requirements or of the context, or, as we shall call it, the domain, is not prescribed or described to the extent that is relied upon in the software design, then it is referred to as an issue of implicit semantics. Once prescribed, respectively described, that issue becomes one of explicit semantics. In this paper we offer **a calculus for analysing & describing domains (i.e., contexts), a calculus that allows you to systematically and formally describe domains.**

1.2 A Triptych of Software Engineering

The dogma is:

- *before software can be designed we must understand its requirements;*
- *and before we can prescribe the requirements we must understand the domain, that is, describe the domain.*

A strict, but not a necessary, interpretation of this dogma thus suggests that software development “ideally” proceeds in three phases:

- First a phase of **domain engineering** in which an analysis of the application domain leads to a description of that domain.¹

¹This phase is often misunderstood. On one hand we expect domain stakeholders, e.g., *bank* associations and university economics departments, to establish “a family” of *bank* domain descriptions: taught when training and educating new employees, resp. students. Together this ‘family’ covers as much as is known about *banking*. On the other hand we expect each new *bank* application (software) development to “carve” out a “sufficiently large” description of the domain it is to focus on. Please replace the term *bank* with an appropriate term for the domain for which You are to develop software.

- Then a phase of **requirements engineering** in which an analysis of the domain description leads to a prescription of requirements to software for that domain.
- And, finally, a phase of **software design** in which an analysis of the requirements prescription leads to software for that domain.

Proof of program, i.e., software code, correctness can be expressed as:

- $\mathcal{D}, \mathcal{S} \models \mathcal{R}$

which we read as: proofs that \mathcal{S} software is correct with respect to \mathcal{R} requirements implies references to the \mathcal{D} domain.

1.3 Contexts [1] \equiv Domains [26]

Often the domain is referred to as the **context**. We treat contexts, i.e., domain descriptions as first class citizens [1, Abstract, Page 1, lines 9–10]. By emphasizing the formalisation of domain descriptions we thus focus on the *explicit* semantics. Our approach, [26], summarised in Sect. 2 of this paper, thus represents a formal approach to the description of contexts (i.e., domains) [1, Abstract, Page 1, line 12]. By a **domain**, i.e., a context, **description**, we shall here understand an **explicit semantics** of what is usually not specified and, when not so, referred to as **implicit semantics**².

1.4 Semantics

I use the term ‘semantics’ rather than the term ‘knowledge’. The reason is this: The entities are what we can meaningfully speak about. That is, the names of the endurants and perdurants, of their being atomic or composite, discrete or continuous, parts, components or materials, their unique identifications, mereologies and attributes, and the types, values and use of operations over these, form the language spoken by practitioners in the domain. It is this language its base syntactic quantities and semantic domains we structure and ascribe a semantics.

1.5 Method & Methodology

By a **method** I understand a set of principles for selecting and applying techniques and tools for constructing a manifest or an abstract artifact. By **methodology** I understand the study and knowledge of methods. **My work is almost exclusively in the area of methods and methodology.**

1.6 Computer & Computing Sciences

By **computer science** I understand the study and knowledge about the things that can exist inside computing devices.

By **computing science** I understand the study and knowledge about how to construct the things that can exist inside computing devices. Computing science is also often referred to as *programming methodology*. **My work is almost exclusively in the area of computing science.**

²“The contexts . . . are treated as second-class citizens: in general, the modelling is implicit and usually distributed between the requirements model and the system model.” [1, Abstract, Page 1, lines 9–12].

1.7 Software and Systems Engineering

By **software engineering** I understand the triplet of **domain engineering**, **requirements engineering**, and **software design**. My work has almost exclusively been in the area of methodologies for large scale software – beginning with compilers (CHILL and Ada, [34, 30, 28, 31, 41]).

2 The Analysis & Description Prompts

We present a calculus of analysis and description prompts³. The presentation here is a very short, 12 pages, version of [26, Sects. 2–4, 31 pages]. These prompts are tools that the domain analyser & describer uses. The domain analyser & describer is in the domain, sees it, can touch it, and then applies the prompts, in some orderly fashion, to what is being observed. So, on one hand, there is the necessarily informal domain, and, on the other hand, there are the seemingly formal prompts and the “*suggestions for something to be said*”, i.e., written down: narrated and formalised. See Fig. 1. The figure suggests

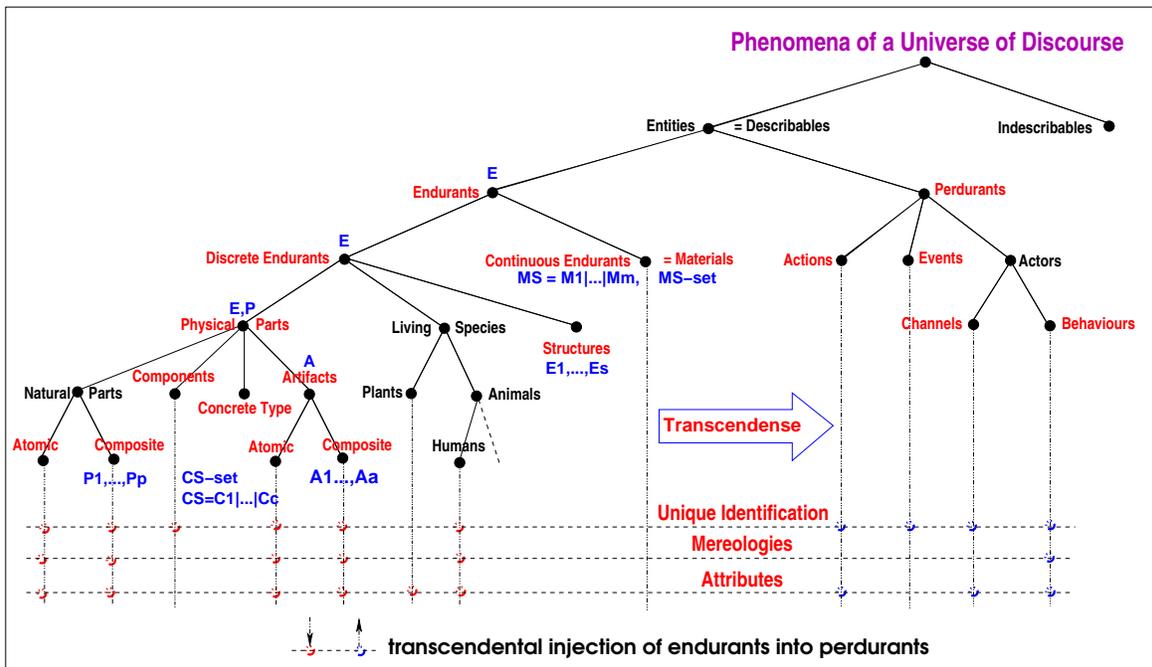


Figure 1: An Ontology for Manifest Domains

a number of **analysis** and **description** prompts. The domain analyser & describer is “positioned” at the top, the “root”. If what is observed can be conceived and described then it **is an entity**. If it can be described as a “complete thing” at no matter which given snapshot of time then it **is an endurant**. If it is an entity but for which only a fragment exists if we look at or touch them at any given snapshot in time, then it **is a perdurant**.

The concepts of *endurants* and *perdurants* may seem novel to some readers. So we elaborate a bit. First we must recall that we are trying to describe aspects a real worlds. That is, to model, in narrative

³Prompt, as a verb: to move or induce to action; to occasion or incite; inspire; to assist (a person speaking) by “*suggesting something to be said*”.

and in formal terms, what has puzzled philosophers since antiquity. One can therefore not expect to define the terms ‘*endurants*’ and ‘*perdurants*’ as one define terms in computer science and mathematics. Here, then are some “definitions”, i.e. some delineations, some “encirclings” of crucial concepts.

Definition 1 Entity: *By an entity we shall understand a phenomenon, i.e., something that can be observed, i.e., be seen or touched by humans, or that can be conceived as an abstraction of an entity; alternatively, a phenomenon is an entity, if it exists, it is “being”, it is that which makes a “thing” what it is: essence, essential nature [40, Vol. I, pg. 665].*

Definition 2 Endurant: *By an endurant we shall understand an entity that can be observed or conceived and described as a “complete thing” at no matter which given snapshot of time; alternatively an entity is endurant if it is capable of enduring, that is persist, “hold out” [40, Vol. I, pg. 656]. Were we to “freeze” time we would still be able to observe the entire endurant .*

Definition 3 Perdurant: *By a perdurant we shall understand an entity for which only a fragment exists if we look at or touch them at any given snapshot in time, that is, were we to freeze time we would only see or touch a fragment of the perdurant, alternatively an entity is perdurant if it endures continuously, over time, persists, lasting [40, Vol. II, pg. 1552] .*

2.1 Endurants: Parts, Components and Materials

Endurants are either **discrete** or **continuous**. With discrete endurants we can choose to associate, or to not associate *mereologies*⁴. If we do we shall refer to them as **parts**, else we shall call them **components**. With continuous endurants we do not associate mereologies. The continuous endurants we shall also refer to as (*gaseous or liquid*) **materials**. Parts are either **atomic** or **composite** and all parts have *unique identifiers, mereology and attributes*. If the observed part, $p:P$, is **is_composite** then we can observe the part sorts and values, P_1, P_2, \dots, P_m respectively p_1, p_2, \dots, p_m of p . “Applying” **observe_part_sorts** to p yields an informal (i.e., a **narrative**) and a **formal** description:

Schema: Composite Parts

- **Narrative:**
 - ◊ ...
 - **Formal:**
 - ◊ **type**
 - ⊗ P_1, P_2, \dots, P_m ,
 - ◊ **value**
 - ⊗ $\text{obs_}P_i: P \rightarrow P_i$,
- repeated for all m part sorts P_i !

Aircraft Example 1: The Pragmatics

The *pragmatics*⁵ of this ongoing example is this: We are dealing with ordinary passenger aircraft. We are focusing on that tiny area of concern that focus on passengers being informed of the progress of the flight, once in the air: where is the aircraft: its current position somewhere above the earth; its current

⁴— ‘mereology’ will be explained next

speed and direction and possible acceleration (or deceleration); We do not bother about what time it is – etc. We abstract from the concrete presentation of this information.

Aircraft **Example 2:** Parts

1 An *aircraft* is composed from several parts of which we focus on

- a a *position* part,
- b a *travel dynamics* part, and
- c a *display* part.

type

1 AC, PP, TD, DP

value

1a obs_PP: AC \rightarrow PP

1b obs_TD: AC \rightarrow TD

1c obs_DP: AC \rightarrow DP

We have just summarised the analysis and description aspects of endurants in *extension* (their “form”). We now summarise the analysis and description aspects of endurants in *intension* (their “contents”). There are three kinds of intensional *qualities* associated with parts, two with components, and one with materials. Parts and components, by definition, have *unique identifiers*; parts have *mereologies*, and all endurants have *attributes*.

2.2 Internal Qualities

2.2.1 Unique Identifiers

Unique identifiers are further undefined tokens that uniquely identify parts and components. The description language observer **uid_P**, when applied to parts $p:P$ yields the unique identifier, $\pi:\Pi$, of p . So the **observe_part_sorts**(p) invocation also yields the description text:

Schema: Unique Identifiers

- ... [added to the narrative and]
- **type**
 - ⊗ $\Pi_1, \Pi_2, \dots, \Pi_m$;
- **value**
 - ⊗ $\text{uid}_{\Pi_i} : P_i \rightarrow \Pi_i$,

repeated for all m part sorts P_i s and added to the formalisation.

Aircraft **Example 3:** Unique Identifiers

2 position, travel dynamic and display parts have unique identifiers.

⁵Pragmatics is here used in the sense outlined in [6, Chapter 7, Pages 145–148].

type 2 PPI, TDI, DPI value 2 uid_PP: PP → PPI 2 uid_TD: TD → TDI 2 uid_DP: DP → DPI
--

2.2.2 Mereology

Mereology is the study and knowledge of parts and part relations. The mereology of a part is an expression over the unique identifiers of the (other) parts with which it is related, hence **mereo_P**: $P \rightarrow \mathcal{E}(\Pi_j, \dots, \Pi_k)$ where $\mathcal{E}(\Pi_j, \dots, \Pi_k)$ is a type expression. So the **observe_part_sorts**(p) invocation also yields the description text:

Schema: Mereology

- | |
|--|
| <ul style="list-style-type: none"> • ... [added to the narrative and] • value <ul style="list-style-type: none"> ⊗ mereo_P_i: $P_i \rightarrow \mathcal{E}_i(\Pi_{i_j}, \dots, \Pi_{i_k})$ [added to the formalisation] |
|--|

Aircraft **Example 4:** Mereology

We shall omit treatment of aircraft mereologies.

- 3 The position part is related to the display part.
- 4 The travel dynamics part is related to the display part.
- 5 The display part is related to both the position and the travel dynamics parts.

value

3 mereo_PP: PP → DPI 4 mereo_TD: TP → DPI 4 mereo_DP: DP → PPI × TDI
--

2.2.3 Attributes

Attributes are the remaining qualities of endurants. The analysis prompt **obs_attributes** applied to an endurant yields a set of type names, A_1, A_2, \dots, A_t , of attributes. They imply the additional description text:

Schema: Attributes

- | |
|---|
| <ul style="list-style-type: none"> • Narrative: <ul style="list-style-type: none"> ⊗ ... • Formal: <ul style="list-style-type: none"> ⊗ type |
|---|

$\otimes A_1, A_2, \dots, A_t$
 \otimes **value**
 \otimes attr_ A_i : $E \rightarrow A_i$
 repeated for all t attribute sorts A_i s !

Aircraft **Example 5:** Position Attributes

6 Position parts have longitude, latitude and altitude attributes.

type

6 LO, LA, AL

value

6 attr_LO: PP \rightarrow LO

6 attr_LA: PP \rightarrow LA

6 attr_AL: PP \rightarrow AL

These quantities: longitude, latitude and altitude are “actual” quantities, they mean what they express, they are not *recordings* or *displays* of these quantities; to express those we introduce separate types.

Aircraft **Example 6:** Travel Dynamics Attributes

7 Travel dynamics parts have velocity⁶ and acceleration⁷.

type

7 VEL, ACC

value

7 attr_VEL: TD \rightarrow VEL

7 attr_ACC: TD \rightarrow ACC

These quantities: velocity and acceleration, are “actual” quantities, they mean what they express, they are not *recordings* or *displays* of these quantities; to express those we introduce separate types.

Aircraft **Example 7:** Quantity Recordings

8 On one hand there are the actual location and dynamics quantities (i.e., values),

9 on the other hand there are their recordings,

10 and there are conversion functions from actual to recorded values.

type

8 LO, LA, AL, VEL, ACC

9 rLO, rLA, rAL, rVEL, rACC

value

10 a2rLO: LO \rightarrow rLO, a2rLA: LA \rightarrow rLA, a2rAL: AL \rightarrow rAL

⁶Velocity is a *vector* of *speed* and *orientation* (i.e., *direction*)

⁷Acceleration is a vector of change of speed per time unit and orientation.

10 a2rVEL: VEL \rightarrow rVEL, a2rACC: ACC \rightarrow rACC

There are, of course, no functions that convert recordings to actual values !

Aircraft **Example 8:** Display Attributes

11 Display parts have display-modified longitude, latitude and altitude, and velocity and acceleration attributes – with functions that convert between these, recorded and displayed, attributes.

type

11 dLO, dLA, dAL

11 dVEL, dACC

value

11 attr.dLO: DP \rightarrow dLO

11 attr.dLA: DP \rightarrow dLA

11 attr.dAL: DP \rightarrow dAL

11 attr.dVEL: DP \rightarrow dVEL

11 attr.dACC: DP \rightarrow dACC

11 r2dLO,d2rLO: rLO \leftrightarrow dLO

11 r2dLA,d2rLA: rLA \leftrightarrow dLA

11 r2dAL,d2rAL: rAL \leftrightarrow dAL

11 r2dVEL,d2rVEL: rVEL \leftrightarrow dVEL

11 r2dACC,d2rACC: rACC \leftrightarrow dACC

axiom

\forall rlo:rLO • d2rLO(r2dLO(rlo))=rlo etcetera !

2.2.4 Attribute Categories

Michael A. Jackson [39] categorizes and defines attributes as either *static* or *dynamic*, with dynamic attributes being either *inert*, *reactive* or *active*. The latter are then either *autonomous*, *biddable* or *programmable*. This categorization has a strong bearing on how these (f.ex., part) attributes are dealt with when now interpreting parts as behaviours.

Aircraft **Example 9:** Attribute Categories

12 Longitude, latitude, altitude, velocity and acceleration are all reactive attributes – they change in response to the bidding of aircraft attributes that we have not covered⁸.

13 Their display modified forms are all programmable attributes.

attribute categories

12 **reactive:** LO,LA,AL,VEL,ACC

13 **programmable:** dLO,dLA,dAL,dVEL,dACC

2.3 Description Axioms and Proof Obligations

In [26] we show that the description prompts may result in axioms or proof obligations. We refer to [26] for details. Here we shall, but show one example of an axiom.

Aircraft **Example 10:** An Axiom

14 The displayed attributes must at any time be displays of the corresponding recorded position and travel dynamics attributes.

axiom

⁸– for example: *thrust*, *weight*, *lift*, *drag*, *rudder position*, and *aileron position* – plus dozens of other – attributes

```

14  □ ∀ ac:AC •
14    let (pp,td,di) = (obs_PP(ac),obs_TD(ac),obs_DP(ac)) in
14    let (lo,la,at) = (attr_LO(pp),attr_LA(pp),attr_AT(pp)),
14      (vel,acc,dir) = (attr_VEL(td),obs_ACC(td)),
14      (dlo,dla,dat) = (attr_dLO(di),attr_dLA(di),attr_dAT(di)),
14      (dvel,dacc) = (attr_dVEL(di),obs_dACC(di)) in
14      (dlo,dla,dat) = (r2dLO(a2rLO(lo)),r2dLA(a2rLA(la)),r2dAL(a2rAL(at)))
14  ∧ (dvel,dacc) = (r2dVEL(a2rVEL(vel)),r2dACC(a2rACC(acc)))
14    end end

```

2.4 From Manifest Parts (Endurants) to Domain Behaviours (Perdurants)

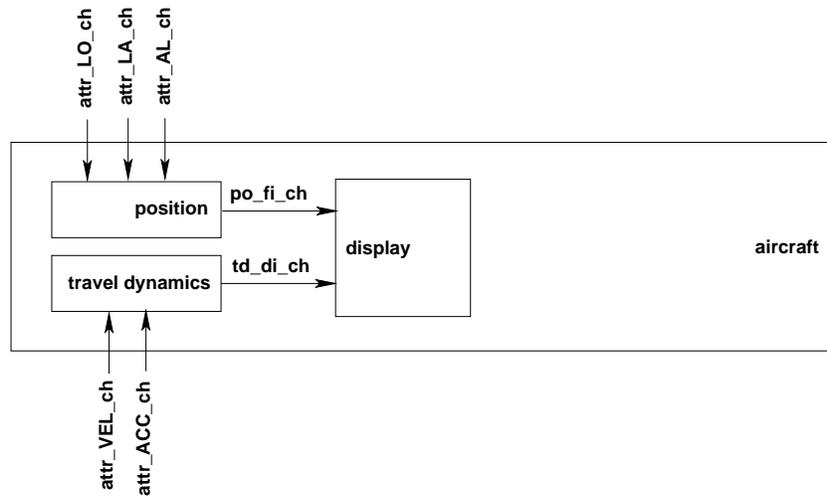
[26] then presents a *compiler* which to manifest *parts* associate *behaviours*. These are then specified as CSP [36] *processes*. We choose CSP [35, 37, 38, 44, 45] for the following reasons: it is a well-established formalism for expressing the behaviour of cooperating sequential processes; it has withstood the test of time: first articles appeared in 1978 and research and industrial use is still at a high; it has a well-founded theory and a *failures-divergence-refinement* proof system with proof rules [43, 32]; we have shown, in [24, To Every Manifest Domain a CSP Expression – A Rôle for Mereology in Computer Science], how to relate a world of space-based endurants with a world of time-based perdurants; in [23, A Philosophy of Domain Science & Engineering –An Interpretation of Kai Sørlander’s Philosophy]. The latter two reasons, to us, are rather convincing: The concept of *mereology* is well-established, both in philosophy and in logic. To “connect” the concepts of mereology with ontological concepts of describable domains, by some neo-Kantian *transcendental deduction* is quite surprising – and pleasing.

2.4.1 The Idea — by means of an example

The term *aircraft* can have the following “meanings”: the *aircraft*, as an *endurant*, parked at the airport gate, i.e., as a *composite part*; the *aircraft*, as a *perdurant*, as it flies through the skies, i.e., as a *behaviour*; and the *aircraft*, as an *attribute*, of an airline timetable.

Aircraft **Example 11**: An Informal Story

An aircraft has the following behaviours: the *position* behaviour; it observes the aircraft location attributes: *longitude*, *latitude* and *altitude*, record and communicate these, as a triple, to the *display* behaviour; the *travel dynamics* behaviour; it observes the aircraft travel dynamics attributes *velocity* and *acceleration*, record and communicate these, as a triple, to the *display* behaviour; and the *display* behaviour receives two doublets of attribute value recordings from respective *position* and *travel dynamics* behaviours and display these recorded attribute values: *longitude*, *latitude*, *altitude*, *velocity* and *acceleration* in some form.



The six actual *position* and *travel dynamics* attribute values *longitude*, *latitude*, *altitude*, *velocity* and *acceleration* are recorded, by appropriate instruments. In the above figure this is indicated by **input** channels `attr_LO_ch`, `attr_LA_ch`, `attr_AL_ch`, `attr_VEL_ch` and `attr_ACC_ch`.

2.4.2 Channels and Communication

Behaviours sometimes synchronise and usually communicate. We use the CSP [36] notation (adopted by RSL) to model behaviour communication. Communication is abstracted as the sending, `ch!m`, and receipt, `ch?`, of messages, `m:M`, over channels, `ch`.

```

type M
channel ch:M

```

Aircraft **Example 12:** Channels

For this example we focus only on communications from the *position* and *travel dynamics* behaviours to the *display* behaviour.

- 15 The messages sent from the *position* behaviour to the *display* behaviour are triplets of recorded longitude, latitude and altitude values.
- 16 The messages sent from the *travel dynamics* behaviour to the *display* behaviour are droplets of recorded velocity and acceleration values.
- 17 There is a channel, `po-di_ch`, that allows communication of messages from the *position* behaviour to the *display* behaviour.
- 18 There is a channel, `td-di_ch`, that allows communication of messages from the *travel dynamics* behaviour to the *display* behaviour.
- 19 For each of the reactive attributes there is a corresponding channel.

type

- 15 $PM = rLO \times rLA \times rAL$
- 16 $TDM = rVEL \times rACC$

channel

17 po_di_ch:PM
 18 td_di_ch:TDM
 19 attr_LO_ch:LO, attr_LA_ch:LA, attr_AL_ch:AL
 19 attr_VEL_ch:VEL, attr_ACC_ch:ACC

2.4.3 Behaviour Signatures

We shall only cover behaviour signatures when expressed in RSL/CSP [33]. The behaviour functions are now called processes. That a behaviour function is a never-ending function, i.e., a process, is “revealed” in the function signature by the “trailing” **Unit**:

behaviour: ... → ... **Unit**

That a process takes no argument is “revealed” by a “leading” **Unit**:

behaviour: **Unit** → ...

That a process accepts channel, viz.: *ch*, inputs, including accesses an external attribute *A*, is “revealed” in the function signature as follows:

behaviour: ... → **in** *ch* ... , resp. **in** *attr_A_ch*

That a process offers channel, viz.: *ch*, outputs is “revealed” in the function signature as follows:

behaviour: ... → **out** *ch* ...

That a process accepts other arguments is “revealed” in the function signature as follows:

behaviour: *ARG* → ...

where *ARG* can be any type expression:

$T, T \rightarrow T, T \rightarrow T \rightarrow T$, etcetera

where *T* is any type expression.

2.4.4 Translation of Part Qualities

Part qualities, that is: *unique identifiers*, *mereologies* and *attributes*, are translated into behaviour arguments – of one kind or another, i.e., (...). Typically we can choose to *index* behaviour names, *b* by the *unique identifier*, *id*, of the part based on which they were translated, i.e., *b_{id}*. *Mereology values* are usually static, and can, as thus, be treated like we treat static attributes (see next), or can be set by their behaviour, and are then treated like we treat programmable attributes (see next), i.e., (...). *Static attributes* become behaviour definition (body) constant values. *Inert*, *reactive* and *autonomous attributes* become references to channels, say *ch_dyn*, such that when an inert, reactive and autonomous attribute value is required it is expressed as *ch_dyn ?*. *Programmable* and *biddable attributes* become arguments which are passed on to the tail-recursive invocations of the behaviour, and possibly updated as specified [with]in the body of the definition of the behaviour, i.e., (...).

2.4.5 Part Behaviour Signatures

We can, without loss of generality, associate with each part a behaviour; parts which share attributes (and are therefore referred to in some parts' mereology), can communicate (their "sharing") via channels. A behaviour signature is therefore:

$$\text{beh}_{\pi:\Pi}: \text{me:MT} \times \text{sa:SA} \rightarrow \text{ca:CA} \rightarrow \mathbf{in} \text{ } \text{ichns}(\text{ea:EA}) \text{ } \mathbf{in, out} \text{ } \text{iochs}(\text{me}) \text{ } \mathbf{Unit}$$

where (i) $\pi:\Pi$ is the unique identifier of part p , i.e., $\pi = \mathbf{uid_P}(p)$, (ii) me:ME is the mereology of part p , $\text{me} = \mathbf{obs_mereo_P}(p)$, (iii) sa:SA lists the static attribute values of the part, (iv) ca:CA lists the biddable and programmable attribute values of the part, (v) $\text{ichns}(\text{ea:EA})$ refer to the external attribute input channels, and where (vi) $\text{iochs}(\text{me})$ are the input/output channels serving the attributes shared between the part p and the parts designated in its mereology me .

We focus, for a little while, on the expression of sa:SA , ea:EA and ca:CA , that is, on the concrete types of SA, EA and CA. sa:SA lists the static value types, (svT_1, \dots, svT_s) , where s is the number of static attributes of parts $p:P$. ea:EA lists the external attribute value channels of parts $p:P$ in the behaviour signature and as input channels, ichns , see 9 lines above. ca:CA lists the controllable value expression types of parts $p:P$. A controllable attribute value expression is an expression involving one or more attribute value expressions of the type of the biddable or programmable attribute .

Aircraft Example 13: Part Behaviour Signatures, I/II

We omit the signature of the aircraft behaviour.

- 20 The signature of the *position* behaviour lists its unique identifier, mereology, no static and no controllable attributes, but its three reactive attributes (as input channels) and its (output) channel to the *display* behaviour.
- 21 The signature of the *travel dynamics* behaviour lists its unique identifier, mereology, no static and no controllable attributes, but its three reactive attributes (as input channels) and its (output) channel to the *display* behaviour.
- 22 The signature of the *display* behaviour lists its unique identifier, its mereology, no static attribute, but the programmable display attributes, assembled in a pair of a triplet and doublets, and its two input channels from the *position*, respectively the *travel dynamics* behaviours.

Aircraft Example 14: Part Behaviour Signatures, I/II

type

22 DA = (dLA × dLO × dAL) × (dVEL × dACC)

value

20 position: PI × DPI →

20 **in** attr_LO_ch, attr_LA_ch, attr_AL_ch, **out** po_di_ch **Unit**

21 travel_dynamics: TDI × DPI →

21 **in** attr_VEL_ch, attr_ACC_ch, attr_DIR_ch, **out** td_di_ch **Unit**

22 display: DI × (PPI × TDI) → DA → **in** po_di_ch, td_di_ch **Unit**

2.4.6 Behaviour Compilations

Composite Behaviours Let P be a composite sort defined in terms of sub-sorts P_1, P_2, \dots, P_n . The process definition compiled from $p:P$, is composed from a process description, $\mathcal{M}cP_{\text{uid}_P(p)}$, relying on and handling the unique identifier, mereology and attributes of part p operating in parallel with processes p_1, p_2, \dots, p_n where p_1 is compiled from $p_1:P_1$, p_2 is compiled from $p_2:P_2$, ..., and p_n is compiled from $p_n:P_n$. The domain description “compilation” schematic below “formalises” the above.

Transcendental Schema: Abstract `is_composite(p)`

value

```

compile_process: P → RSL-Text
compile_process(p) ≡
     $\mathcal{M}P_{\text{uid}_P(p)}(\text{obs\_mereo}_P(p), \mathcal{S}_{\mathcal{A}}(p))(\mathcal{C}_{\mathcal{A}}(p))$ 
    || compile_process(obs_partP1(p))
    || compile_process(obs_partP2(p))
    || ...
    || compile_process(obs_partPn(p))

```

The text macros: $\mathcal{S}_{\mathcal{A}}$ and $\mathcal{C}_{\mathcal{A}}$ were informally explained above. Part sorts P_1, P_2, \dots, P_n are obtained from the `observe_part_sorts` prompt.

Aircraft **Example 15:** Aircraft Behaviour, I/II

- 23 Compiling a composite aircraft part results in the parallel composition
- a the compilation of the atomic position part,
 - b the compilation of the atomic travel dynamics part, and
 - c the compilation of the atomic display part.
- We omit compiling the aircraft core behaviour.
- 24 Compilation of atomic parts entail no further compilations.

Aircraft **Example 15:** Aircraft Behaviour, II/II

value

```

23 compile(ac) ≡
23a   compile(obs_PP(p))
23b   || compile(obs_TD(p))
23c   || compile(obs_DI(p))

```

Atomic Behaviours

Transcendental Schema: `is_atomic(p)`

value

```

compile_process: P → RSL-Text
compile_process(p) ≡

```

$$\mathcal{M}P_{\text{uid}_P(p)}(\text{obs_mereo}_P(p), \mathcal{F}_A(p))(\mathcal{C}_A(p))$$

Aircraft **Example 16:** Atomic Behaviours

25 We initialise the display behaviour with a further undefined value.

value

```

23a compile(obs_PP(p))≡
23a   position(uid_PP(p),mereo_PP(p))
23b compile(obs_TD(p)) ≡
23b   travel_dynamics(uid_TD(p),mereo_TD(p))
25  init_DA:DA = ...
23c compile(obs_DI(p)) ≡
23c   display(.uid_DI(p),mereo_DI(p))(init_DA)

```

In the above we have already subsumed the *atomic behaviour definitions*, see next, and directly inserted the \mathcal{F} definitions.

2.4.7 Atomic Behaviour Definitions

Transcendental Schema IV: Atomic Core Processes

value

```

 $\mathcal{M}P_{\pi:\Pi}$ : me:MT×sa:SA → ca:CA →
  in ichns(ea:EA) in,out iochs(me) Unit
 $\mathcal{M}P_{\pi:\Pi}$ (me,sa)(ca) ≡
  let (me',ca') =  $\mathcal{F}_{\pi:\Pi}$ (me,sa)(ca) in
   $\mathcal{M}P_{\pi:\Pi}$ (me',sa)(ca') end

 $\mathcal{F}_{\pi:\Pi}$ : me:MT×sa:SA → CA →
  in ichns(ea:EA) in,out iochs(me) → MT×CA

```

Aircraft **Example 17:** Position Behaviour Definition

26 The *position* behaviour offers to receive the *longitude*, *latitude* and the *altitude* attribute values

27 and to offer them to the *display* behaviour,

28 whereupon it resumes being the *position* behaviour.

value

```

20 position(pπ,dπ) ≡
26   let (lo,la,al) = (attr_LO_ch?,attr_LA_ch?,attr_AL_ch?) in
27   po_di_ch ! (a2rLO(lo),a2rLA(la),a2rAL(al)) ;
28   position(pπ,dπ) end

```

Aircraft **Example 18:** Travel Dynamics Behaviour Definition

29 The *travel_dynamics* behaviour offers to receive the recorded *velocity* and the *acceleration* attribute values
 30 and to offer these to the *display* behaviour,
 31 whereupon it resumes being the *travel_dynamics* behaviour.

value

```
21 travel_dynamics(td $\pi$ ,d $\pi$ )  $\equiv$ 
29   let (vel,acc)=(attr_VEL_ch?,attr_ACC_ch?) in
30   td_di_ch ! (a2rVEL(vel),a2rACC(acc)) ;
31   travel_dynamics(td $\pi$ ,d $\pi$ ) end
```

Aircraft **Example 19:** Display Behaviour Definition

32 The *display* behaviour offers to receive the reactive attribute doublets from the *position* and the *travel_dynamics* behaviours while
 33 resuming to be that behaviour albeit now with these as their updated display.
 34 The **conversion** functions are extensions of the ones introduced earlier.

value

```
22 display(d $\pi$ ,(d $\pi$ ,td $\pi$ ))(d_pos,d_tdy)  $\equiv$ 
32   let (pos_d',tdy_d') = (po_di_ch?,td_di_ch?) in
33   display(d $\pi$ ,(d $\pi$ ,td $\pi$ ))(conv(pos_d'),conv(c_tdy_d')) end
```

type

```
34 dMPD = dLO  $\times$  dLA  $\times$  dAL
```

```
34 dMTD = dVEL  $\times$  dACC
```

value

```
34 conv: MPD  $\rightarrow$  dMPD
```

```
34 conv(rlo,rla,ral)  $\equiv$  (r2dLO(rlo),r2dLA(rla),r2dAL(ral))
```

```
34 conv: MTD  $\rightarrow$  dMTD
```

```
34 conv(rvel,racc)  $\equiv$  (r2dVEL(rvel),r2dACC(racc))
```

2.5 A Proof Obligation

We refer, again, to [26] for more on proof obligations.

Aircraft **Example 20:** A Proof Obligation

The perdurant descriptions of Items 15–34 is a model of the axiom expressed in Item 14.

3 Calculations in Classical Domains: Some Simple Observations

This section covers three loosely related topics: Sect. 3.1 muses over properties of some attribute values. Then, Sect. 3.2 we recall some facts about types, scales and values of measurable units in physics. The previous leads us, in Sect. 3.3 to consider further detailing the concept of attributes such as we have covered it in Sect. 2.2.3, Pages and in [26]. The reason for covering these topics is that most attribute values are represented in “final” programs as numbers of one kind or another and that type checking in most software is with respect to these numbers.

3.1 Some Observations on Some Attribute Values

Let us, seemingly randomly, examine some simple, e.g., arithmetic, operations in classical domains. By *time* is often meant absolute time. So a time could be *May 16, 2018: 00:27 am*. One can not add two times. One can speak of a time being earlier, or before another time. *October 23, 2017: 10:01 am* is earlier, \leq , than *May 16, 2018: 00:27 am*. One can speak of the time interval between *October 23, 2016: 8:01 am* and *October 24, 2017: 10:05 am* being *1 year, 1 day, 2 hours and 4 minutes*, that is: *October 24, 2017: 10:05 am* \ominus *October 23, 2016: 8:01 am* = *1 year, 1 day, 2 hours and 4 minutes* One can add a *time interval* to a *time* and obtain a *time*. One can multiply a *time interval* with a *real*⁹ We can formalize the above:

type $\mathbb{T} = \text{Month} \times \text{Day} \times \text{Year} \times \text{Hour} \times \text{Minute} \times \text{Sec} \dots$ $\mathbb{TI} = \text{Days} \times \text{Hours} \times \text{Minutes} \times \text{Seconds} \times \dots$ $\text{Month} = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$ $\text{Day} = \{1, 2, 3, 4, \dots, 28, 29, 30, 31\}$ $\text{Hour, Hours} = \{0, 1, 2, 3, \dots, 21, 22, 23\}$ $\text{Minute, Minutes} = \{0, 1, 2, 3, \dots, 56, 57, 58, 59\}$ $\text{Second, Seconds} = \{0, 1, 2, 3, \dots, 56, 57, 58, 59\}$...	Days = Nat value $\langle, \leq, =, \geq, \rangle: \mathbb{T} \times \mathbb{T} \rightarrow \mathbf{Boole}$ $-: \mathbb{T} \times \mathbb{T} \rightarrow \mathbb{TI} \text{ pre } t-t': t' \leq t$ $\langle, \leq, =, \geq, \rangle: \mathbb{TI} \times \mathbb{TI} \rightarrow \mathbf{Bool}$ $-, +: \mathbb{TI} \times \mathbb{TI} \rightarrow \mathbb{TI}$ $*: \mathbb{TI} \times \mathbf{Real} \rightarrow \mathbb{TI}$ $/: \mathbb{TI} \times \mathbb{TI} \rightarrow \mathbf{Real}$
--	--

One can not add temperatures – makes no sense in physics ! But one can take the mean value of two (or more) temperatures. One can subtract temperatures obtaining positive or negative temperature intervals. One can take the mean of any number of temperature, but would probably be well advised to have these represent regular sampling, or at least time-stamped. One can also define *rate of change of temperature*.

type $\text{Temp, MeanTemp, Degrees, TempIntv} = \text{Degrees}$
value $\text{mean: Temp-set} \times \mathbf{Nat} \rightarrow \text{MeanTemp}$ $-: \text{Temp} \times \text{Temp} \rightarrow \text{TempIntv}$
type $\text{TST} = (\text{Temp} \times \mathbb{T})\text{-set}$
value $\text{avg: TST} \rightarrow \text{MeanTemp}$

⁹The time interval could, e.g., be converted into seconds, then the integer number standing for seconds can be multiplied by r and the result be converted “back” into years, days, hours, minutes and seconds — whatever it takes !

type

TimeUnit = {"year", "month", "day", "hour", ...}
 RoTC = Templtv × TimeUnit

Etcetera. We leave it to the reader to speculate on which operations one can perform on a persons' attributes: height, weight, birth date, name, etc. And similarly for other domains. It is time to “lift” these observations. After the examples above we should inquire as to which kind of units we may operate upon. For the sake of our later exposition it is enough that we look in some detail at the “universe” of physics.

3.2 Physics Attributes

3.2.1 SI: The International System of Quantities

In physics we operate on values of attributes of manifest, i.e., physical phenomena. The type of some of these attributes are recorded in well known tables, cf. Tables 1–3.

Table 1 shows the base units of physics.

Base quantity	Name	Type
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 1: Base Units

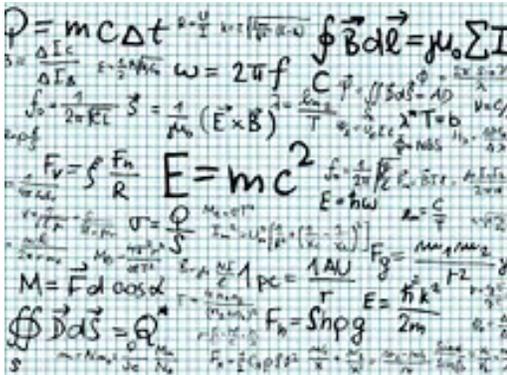
Table 2 on the following page shows the units of physics derived from the base units.

Table 3 on page 19 shows further units of physics derived from the base units.

Table 4 on page 19 shows standard prefixes for SI units of measure.

Table 5 on page 20 shows fractions of SI units of measure.

These “pictures” are meant as an eye opener, a “teaser”.



And these formulas likewise !

Name	Type	Derived Quantity	Derived Type
radian	rad	angle	m/m
steradian	sr	solid angle	$m^2 \times m^{-2}$
Hertz	Hz	frequency	s^{-1}
newton	N	force, weight	$kg \times m \times s^{-2}$
pascal	Pa	pressure, stress	N/m^2
joule	J	energy, work, heat	$N \times m$
watt	W	power, radiant flux	J/s
coulomb	C	electric charge	$s \times A$
volt	V	voltage, electromotive force	W/A ($kg \times m^2 \times s^{-3} \times A^{-1}$)
farad	F	capacitance	C/V ($kg^{-1} \times m^{-2} \times s^4 \times A^2$)
ohm	Ω	electrical resistance	V/A ($kg \times m^2 \times s^3 \times A^2$)
siemens	S	electrical conductance	A/V ($kg^{-1} \times m^{-2} \times s^3 \times A^2$)
weber	Wb	magnetic flux	$V \times s$ ($kg \times m^2 \times s^{-2} \times A^{-1}$)
tesla	T	magnetic flux density	Wb/m^2 ($kg \times s^2 \times A^{-1}$)
henry	H	inductance	Wb/A ($kg \times m^2 \times s^{-2} \times A^2$)
degree Celsius	$^{\circ}C$	temperature relative to 273.15 K	K
lumen	lm	luminous flux	$cd \times sr$ (cd)
lux	lx	illuminance	lm/m^2 ($m^2 \times cd$)

Table 2: Derived Units

$$\begin{array}{ll}
 \text{Efficiency} = \frac{W}{Q_h} & \rho = \frac{m}{V} \\
 \frac{Q_c}{Q_h} = \frac{T_c}{T_h} & P = \frac{F}{A} \\
 \text{Efficiency} = 1 - \left(\frac{Q_c}{Q_h} \right) = 1 - \left(\frac{T_c}{T_h} \right) & \Delta P = \rho gh \\
 \text{Coefficient of performance} = \frac{Q_h}{W} & F_{\text{buoyancy}} = W_{\text{water displaced}} \\
 \text{Coefficient of performance} = \frac{1}{1 - \left(\frac{Q_c}{Q_c + Q_h} \right)} = \frac{1}{1 - \left(\frac{T_c}{T_c + T_h} \right)} & \rho_1 A_1 v_1 = \rho_2 A_2 v_2 \\
 & P_1 + \frac{1}{2} \rho v_1^2 + \rho g y_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g y_2
 \end{array}$$

Carnot Engine

Bernoulli Flow

The point in bringing this material is that when modelling, i.e., describing domains we must be extremely careful in not falling into the trap of modelling physics, etc., types as we do in programming !

3.2.2 What Are We to Learn from this Exposition ?

We see from the previous section , Sect. 3.2, that physics units can be highly “structured”¹⁰. What Are We to Learn from this Exposition ? I think it is this: It is customary, in programs of languages from Algol 60 via Pascal to Java, to assign float or double¹¹ types, as in Java, to [constants or] variables that for example represent values of physics. *So rather completely different types of physics units are all cast into a same, simple-minded, “number” type. No chance, really, for any meaningful type checking.*

¹⁰For example, Newton: $kg \times m \times s^{-2}$, Volt = $kg \times m^2 \times s^{-3} \times A^{-1}$, etc.

¹¹representing single-, resp. double-precision 32-bit IEEE 754 floating point values

Name	Explanation	Derived Type
area	square meter	m ²
volume	cubic meter	m ³
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s ²
wave number	reciprocal meter	m ⁻¹
mass density	kilogram per cubic meter	kg/m ³
specific volume	cubic meter per kilogram	m ³ /kg
current density	ampere per square meter	A/m ²
magnetic field strength	ampere per meter	A/m
amount-of-substance concentration	mole per cubic meter	mol/m ³
luminance	candela per square meter	cd/m ²
mass fraction	kilogram per kilogram	kg/kg = 1

Table 3: Further Units

Prefix name	deca	hecto	kilo	mega	giga	tera	peta	exa	zetta	yotta	
Prefix symbol	da	h	k	M	G	T	P	E	Z	Y	
Factor	10 ⁰	10 ¹	10 ²	10 ³	10 ⁶	10 ⁹	10 ¹²	10 ¹⁵	10 ¹⁸	10 ²¹	10 ²⁴

Table 4: Standard Prefixes for SI Units of Measure

3.3 Attribute Types, Scales and Values: Some Thoughts

This section further elaborates on the treatment of attributes given in Sect. 2.2.3, Pages 6–8. The elaboration is only sketched. It need be studied, in detail.

The elaboration is this: The *attr_A* observer function, for a part *p* of sort P, such as defined in Sect. 2.2.3 (Page 7) yields values of type A. In the revised understanding of attributes the *attr_A* observer is now to yield both the type, AT, and the value, AV, of attribute A:

type

AT, AV

value

attr_A: P → AT × AV

You may think of A being defined by AT × AV.

The revision is further that a domain analysis & description of the operations over attributes values, θ :

$$\theta: A_i \times A_j \times \dots \times A_k \rightarrow V$$

be carefully checked – such as hinted at in Sect. 3.1 on page 16.

Whether such operator-checks be researched and documented “once-and-for-all” for given “standard” domains, by domain scientists, or per domain model, by domain engineers, in connection with specific software development projects is left for you to decide ! These operator-checks, together with an otherwise appropriate domain analysis & description, **if not pursued, results in implicit semantics, and if pursued, results in explicit semantics.** It is as simple as that !

Prefix name	deci	centi	milli	micro	nano	pico	femto	atto	zepto	yocto	
Prefix symbol	d	c	m	μ	n	p	f	a	z	y	
Factor	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}	10^{-21}	10^{-24}

Table 5: Fractions

4 Conclusion

4.1 What Have We Achieved ?

We have suggested that the issue of implicit semantics [1] be resolved by providing a carefully analysed and described domain model [26] prior to requirements capture and software design, a both informally annotated and formally specified model that goes beyond [26] in its treatment of attributes in that these are now endowed with types [and possibly scales (or fractions)] and that each specific domain model analyses and formalises the constraints that operations upon attribute values are carefully analysed, statically.

4.2 Domain Descriptions as Basis for Requirements Prescriptions

This paper covers but one aspect of software development.

- [17] covers additional facets of domain analysis & description.
- [19] offers a systematic approach to requirements engineering based on domain descriptions. It is this approach that justifies our claim that domain modelling “*alleviate the issue of implicit semantics.*”
- [16] presents an operational/denotational semantics of the manifest domain analysis & description calculus of [26].
- [24]¹² shows that to every manifest mereology there corresponds a CSP expression.
- [18] muses over issues of software simulators, demos, monitors and controllers.

4.3 What Next ?

Well, there is a lot of fascinating research to be done now. Studying analysis & description techniques for attribute types, values and constraints. And for engineering their support.

4.4 Thanks

to J. Paul Gibson and Dominique Méry for inviting me, to J. Paul Gibson for organising my flights, hotel and registration, and to Dominique Méry for his patience in waiting for my written contribution.

5 Bibliographical Notes

5.1 References to Draft Domain Descriptions

¹²Accepted for publication in *Journal of Logical and Algebraic Methods in Programming*, 2018.

- Swarms of Drones [21]
- Urban Planning [29]
- Documents [22]
- Credit Cards [15]
- Weather Information Systems [20]
- The Tokyo Stock Exchange [25]
- Pipelines [12]
- Road Transportation [13]
- Transaction-based Web Software [10]
- "The Market" [4]
- Container [Shipping] Lines [7]
- Railway Systems [3, 27, 5, 42, 46]

I apologise for the numerous references to own reports and publications.

References

- [1] Yamine Aït Ameur, J. Paul Gibson & Dominique Méry (2014): *On Implicit and Explicit Semantics: Integration Issues in Proof-Based Development of Systems*. In: *Leveraging Applications of Formal Methods, Verification and Validation. Specialized Techniques and Applications - 6th International Symposium, ISO LA 2014, Imperial, Corfu, Greece, October 8-11, 2014, Proceedings, Part II*, pp. 604–618, doi:10.1007/978-3-662-45231-8_50.
- [2] Yamine Aït Ameur & Dominique Méry (2016): *Making explicit domain knowledge in formal system development*. *Sci. Comput. Program.* 121, pp. 100–127, doi:10.1016/j.scico.2015.12.004.
- [3] Dines Bjørner (2000): *Formal Software Techniques in Railway Systems*. In Eckehard Schnieder, editor: *9th IFAC Symposium on Control in Transportation Systems*, VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik, VDI-Gesellschaft für Fahrzeug- und Verkehrstechnik, Technical University, Braunschweig, Germany, pp. 1–12. Invited talk.
- [4] Dines Bjørner (2002): *Domain Models of "The Market" — in Preparation for E-Transaction Systems*. In: *Practical Foundations of Business and System Specifications (Eds.: Haim Kilov and Ken Baclawski)*, Kluwer Academic Press, The Netherlands. Final draft version. <http://www2.imm.dtu.dk/db/themarket.pdf>.
- [5] Dines Bjørner (2003): *Dynamics of Railway Nets: On an Interface between Automatic Control and Software Engineering*. In: *CTS2003: 10th IFAC Symposium on Control in Transportation Systems*, Elsevier Science Ltd., Oxford, UK, doi:10.1016/S1474-6670(17)32424-2. Symposium held at Tokyo, Japan. Editors: S. Tsugawa and M. Aoki. Final version. <http://www2.imm.dtu.dk/db/ifac-dynamics.pdf>.
- [6] Dines Bjørner (2006): *Software Engineering, Vol. 2: Specification of Systems and Languages*. Texts in Theoretical Computer Science, the EATCS Series, Springer. Chapters 12–14 are primarily authored by Christian Krog Madsen.
- [7] Dines Bjørner (2007): *A Container Line Industry Domain*. Techn. Report, Fredsvej 11, DK-2840 Holte, Denmark. Extensive Draft. <http://www2.imm.dtu.dk/db/container-paper.pdf>.
- [8] Dines Bjørner (2008): *From Domains to Requirements*. In: *Montanari Festschrift, Lecture Notes in Computer Science (eds. Pierpaolo Degano, Rocco De Nicola and José Meseguer)* 5065, Springer, Heidelberg, pp. 1–30.
- [9] Dines Bjørner (2010): *Domain Engineering*. In Paul Boca & Jonathan Bowen, editors: *Formal Methods: State of the Art and New Directions*, Eds. Paul Boca and Jonathan Bowen, Springer, London, UK, pp. 1–42, doi:10.1007/978-1-84882-736-3_1.
- [10] Dines Bjørner (2010): *On Development of Web-based Software: A Divertimento of Ideas and Suggestions*. Technical, Technical University of Vienna. [Http://www.imm.dtu.dk/~dibj/wfdftp.pdf](http://www.imm.dtu.dk/~dibj/wfdftp.pdf).
- [11] Dines Bjørner (2011): *Domains: Their Simulation, Monitoring and Control – A Divertimento of Ideas and Suggestions*. In: *Rainbow of Computer Science, Festschrift for Hermann Maurer on the Occasion of His 70th Anniversary*, Festschrift (eds. C. Calude, G. Rozenberg and A. Saloma), Springer, Heidelberg, Germany, pp. 167–183.

- [12] Dines Bjørner (2013): *Pipelines – a Domain Description*. <http://www.imm.dtu.dk/~dibj/pipe-p.pdf>. Experimental Research Report 2013-2, DTU Compute and Fredsvej 11, DK-2840 Holte, Denmark.
- [13] Dines Bjørner (2013): *Road Transportation – a Domain Description*. <http://www.imm.dtu.dk/~dibj/road-p.pdf>. Experimental Research Report 2013-4, DTU Compute and Fredsvej 11, DK-2840 Holte, Denmark.
- [14] Dines Bjørner (2014): *Domain Analysis: Endurants – An Analysis & Description Process Model*. In Shusaku Iida, José Meseguer & Kazuhiro Ogata, editors: *Specification, Algebra, and Software: A Festschrift Symposium in Honor of Kokichi Futatsugi*, Springer.
- [15] Dines Bjørner (2016): *A Credit Card System: Uppsala Draft*. Technical Report: Experimental Research, Fredsvej 11, DK-2840 Holte, Denmark. [Http://www.imm.dtu.dk/~dibj/2016/credit/accs.pdf](http://www.imm.dtu.dk/~dibj/2016/credit/accs.pdf).
- [16] Dines Bjørner (2016): *Domain Analysis and Description – Formal Models of Processes and Prompts*. Extensive revision of [14]. <http://www.imm.dtu.dk/~dibj/2016/process/process-p.pdf>.
- [17] Dines Bjørner (2016): *Domain Facets: Analysis & Description*. Extensive revision of [9]. <http://www.imm.dtu.dk/~dibj/2016/facets/faoc-facets.pdf>.
- [18] Dines Bjørner (2016): *Domains: Their Simulation, Monitoring and Control – A Divertimento of Ideas and Suggestions*. Technical Report, Fredsvej 11, DK-2840 Holte, Denmark. Extensive revision of [11]. <http://www.imm.dtu.dk/~dibj/2016/demos/faoc-demo.pdf>.
- [19] Dines Bjørner (2016): *From Domain Descriptions to Requirements Prescriptions – A Different Approach to Requirements Engineering*. Extensive revision of [8].
- [20] Dines Bjørner (2016): *Weather Information Systems: Towards a Domain Description*. Technical Report: Experimental Research, Fredsvej 11, DK-2840 Holte, Denmark. [Http://www.imm.dtu.dk/~dibj/2016/wis/wis-p.pdf](http://www.imm.dtu.dk/~dibj/2016/wis/wis-p.pdf).
- [21] Dines Bjørner (2017): *A Space of Swarms of Drones*. Research Note. [Http://www.imm.dtu.dk/~dibj/2017/docs/docs.pdf](http://www.imm.dtu.dk/~dibj/2017/docs/docs.pdf).
- [22] Dines Bjørner (2017): *What are Documents?* Research Note. [Http://www.imm.dtu.dk/~dibj/2017/docs/docs.pdf](http://www.imm.dtu.dk/~dibj/2017/docs/docs.pdf).
- [23] Dines Bjørner (2018): *A Philosophy of Domain Science & Engineering – An Interpretation of Kai Sørlander’s Philosophy*. Research Note. <http://www.imm.dtu.dk/~dibj/2018/philosophy/filo.pdf>.
- [24] Dines Bjørner (2018): *To Every Manifest Domain a CSP Expression — A Rôle for Mereology in Computer Science*. *Journal of Logical and Algebraic Methods in Programming* (94), pp. 91–108, doi:10.1016/j.jlamp.2017.09.005.
- [25] Dines Bjørner (January and February, 2010): *The Tokyo Stock Exchange Trading Rules*. R&D Experiment, Fredsvej 11, DK-2840 Holte, Denmark. Version 1. <http://www2.imm.dtu.dk/db/todai/tse-1.pdf>, Version 2. <http://www2.imm.dtu.dk/db/todai/tse-2.pdf>.
- [26] Dines Bjørner (Online: July 2016, Journal: March 2017): *Manifest Domains: Analysis & Description*. *Formal Aspects of Computing* 29(2), pp. 175–225, doi:10.1007/s00165-016-0385-z.
- [27] Dines Bjørner, Chris W. George & Søren Prehn (2002): *Computing Systems for Railways — A Rôle for Domain Engineering. Relations to Requirements Engineering and Software for Control Applications*. In: *Integrated Design and Process Technology*. Editors: Bernd Kraemer and John C. Petterson, Society for Design and Process Science, P.O.Box 1299, Grand View, Texas 76050-1299, USA. Extended version. <http://www2.imm.dtu.dk/db/pasadena-25.pdf>.
- [28] Dines Bjørner & Ole N. Oest, editors (1980): *Towards a Formal Description of Ada*. LNCS 98, Springer.
- [29] Dines Bjørner (2017): *Urban Planning Processes*. Research Note. [Http://www.imm.dtu.dk/~dibj/2017/up/urban-planning.pdf](http://www.imm.dtu.dk/~dibj/2017/up/urban-planning.pdf).
- [30] C.C.I.T.T. (1980): *The Specification of CHILL*. Technical Report Recommendation Z200, International Telegraph and Telephone Consultative Committee, Geneva, Switzerland.

- [31] G.B. Clemmensen & O. Oest (1984): *Formal Specification and Development of an Ada Compiler – A VDM Case Study*. In: *Proc. 7th International Conf. on Software Engineering, 26.-29. March 1984, Orlando, Florida*, IEEE, pp. 430–440.
- [32] Computing Laboratory, University of Oxford, England (2003): *FDR4: The CSP Refinement Checker*. Published on the Internet: <https://www.cs.ox.ac.uk/projects/fdr/>.
- [33] Chris W. George, Peter Haff, Klaus Havelund, Anne Elisabeth Haxthausen, Robert Milne, Claus Bendix Nielsen, Søren Prehn & Kim Ritter Wagner (1992): *The RAISE Specification Language*. The BCS Practitioner Series, Prentice-Hall, Hemel Hempstead, England.
- [34] P. Haff & A.V. Olsen (1987): *Use of VDM within CCITT*. In: *VDM – A Formal Method at Work*, eds. Dines Bjørner, Cliff B. Jones, Micheal Mac an Airchinnigh and Erich J. Neuhold, Springer, Lecture Notes in Computer Science, Vol. 252, pp. 324–330. Proc. VDM-Europe Symposium 1987, Brussels, Belgium.
- [35] C.A.R. Hoare (1978): *Communicating Sequential Processes*. *Communications of the ACM* 21(8).
- [36] C.A.R. Hoare (1985): *Communicating Sequential Processes*. C.A.R. Hoare Series in Computer Science, Prentice-Hall International. Published electronically: <http://www.usingcsp.com/cspbook.pdf> (2004).
- [37] C.A.R. Hoare (1985): *Communicating Sequential Processes*. C.A.R. Hoare Series in Computer Science, Prentice-Hall International.
- [38] C.A.R. Hoare (2004): *Communicating Sequential Processes*. Published electronically: <http://www.-usingcsp.com/cspbook.pdf>. Second edition of [37]. See also <http://www.usingcsp.com/>.
- [39] Michael A. Jackson (1995): *Software Requirements & Specifications: a lexicon of practice, principles and prejudices*. ACM Press, Addison-Wesley, Reading, England.
- [40] W. Little, H.W. Fowler, J. Coulson & C.T. Onions (1973, 1987): *The Shorter Oxford English Dictionary on Historical Principles*. Clarendon Press, Oxford, England. Two vols.
- [41] Ole N. Oest (1986): *VDM From Research to Practice (Invited Paper)*. In: *IFIP Congress*, pp. 527–534.
- [42] Martin Pěnička, Alben Kirilova Strupchanska & Dines Bjørner (2003): *Train Maintenance Routing*. In: *FORMS'2003: Symposium on Formal Methods for Railway Operation and Control Systems*, L'Harmattan Hongrie. Conf. held at Techn.Univ. of Budapest, Hungary. Editors: G. Tarnai and E. Schnieder, Germany. Final version. <http://www2.imm.dtu.dk/db/martin.pdf>.
- [43] A. W. Roscoe (1994): *Model checking CSP*, pp. 353–378. Prentice-Hall Intl.
- [44] A. W. Roscoe (1997): *Theory and Practice of Concurrency*. C.A.R. Hoare Series in Computer Science, Prentice-Hall. Now available on the net: <http://www.comlab.ox.ac.uk/people/bill.roscoe/publications/-68b.pdf>.
- [45] Steve Schneider (2000): *Concurrent and Real-time Systems — The CSP Approach*. Worldwide Series in Computer Science, John Wiley & Sons, Ltd., Baffins Lane, Chichester, West Sussex PO19 1UD, England.
- [46] Alben Kirilova Strupchanska, Martin Pěnička & Dines Bjørner (2003): *Railway Staff Rostering*. In: *FORMS2003: Symposium on Formal Methods for Railway Operation and Control Systems*, L'Harmattan Hongrie. Conf. held at Techn.Univ. of Budapest, Hungary. Editors: G. Tarnai and E. Schnieder, Germany. Final version. <http://www2.imm.dtu.dk/db/alben.pdf>.