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| DRAFT SPECIFICATION AND USER’S GUIDE |
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# Preliminaries

## Status of this document

This document is <http://purl.obolibrary.org/obo/bfo/2012-07-20/Reference>

This version of BFO represents a major update to BFO and is not strictly backwards compatible with BFO 1.1. The previous OWL version of BFO, version 1.1.1 will remain available at http://ifomis.org/bfo/1.1 and will no longer be updated. We expect to provide automated support for migrating from BFO 1.1 to BFO 2 at some point in the future.

This version is a draft release for public comments. The release is the product of intensive discussions initiated with a workshop held in Buffalo November 2011.

While we have attempted to produce OWL, FOL and CLIF files reflecting the current BFO2 specification document, there may be issues or bugs that will be fixed in subsequent releases. In addition, there may be changes to the reference before we have the first release candidate.

For more information please see the development site: <http://code.google.com/p/bfo>

SAY SOMETHING ABOUT HOW QUANTIFICATION IS TO BE UNDERSTOOD. ARE FREE VARIABLES UNIVERSALLY QUANTIFIED? (I RECOMMEND WE DON’T USE THAT CONVENTION AND INSTEAD EXPLICITYLY QUANTIFY IN ALL CASES)

The document provides guidance as to how BFO should be used, and also arguments as to why specific choices have been made in the BFO 2.0 architecture. The identifier in brackets is included to enable cross-references back to this document for implementations of BFO in various languages and formats.

BFO 2.0 will exist in various implementations, including FOL, with a version using the CLIF Common Language Interchange Format, and OWL 2. This document provides axioms and theorems in English that easily maps to FOL and so is the direct basis for the CLIF implementations. From this, the OWL implementation will be derived in turn.

# Introduction

This document is a guide for those using Basic Formal Ontology (BFO) as an upper-level (formal, domain-neutral) ontology to support the creation of lower-level domain ontologies.

A *domain* is a portion of reality that forms the subject-matter of a single science or technology or mode of study; for example the domain of plant anatomy, of military targeting, of canon law. (Warning: We also use ‘Domain’ in the specification of BFO relations in what follows to refer to the type of entity which can serve as the subject – first term – of a relation.) BFO is designed to be neutral with regard to the domains to which it is applied in order to support the interoperation of what are called ‘domain ontologies’ defined on its basis and thus to support consistent annotation of data across different domains.

Some domains – such as military targeting – operate primarily with common-sense terms such as ‘weapon’ or ‘target’. Other domains – such as photodermatology – operate primarily with scientific terms such as ‘photon’ or ‘skin biopsy’. BFO’s goal is to provide a common basis for the creation of ontologies relating to both of these types of domains, as well as to mixed domains – by far the most common case – where both sorts of terms are used simultaneously.

BFO supports formal (= logical) reasoning, and is associated with a set of common formal theories (for example of mereotopology [5] and of qualitative spatial reasoning [18], potentially also of numbers [86]) – theories which do not need to be redeveloped for each successive domain.

BFO must be capable of serving as the starting point and architectural basis for the creation of domain ontologies at lower levels, and in what follows we document how such application is to be effected. We describe the conditions which must be satisfied by entities of given sorts if they are properly to be categorized as instantiating the different universals or types (we use these terms interchangeably in what follows) recognized by BFO. To specify these conditions we will utilize a semi-formalized English that has approximately the expressivity of first-order logic (FOL) with identity. We use ‘category’ to refer to those universals at the most general and domain-neutral level. BFO treats only of categories in this sense. A *category* is a formal (= domain-neutral) universal, as contrasted with the material (= domain-specific) universals represented in one or other domain ontology. BFO:*fiat object part* is a category in this sense; not however *photon* or *weapon*,or *mortgage contract*. Spatial, temporal and spatiotemporal region terms are counted as representing formal universals in this sense, since they apply in all domains.

Literature citations are provided for purposes of preliminary orientation only. Thus axioms and definitions included in cited literature are not necessarily in conformity with the content of this document. In particular, there have been, over the years, a number of attempts at formal expression of BFO. This document supersedes those.

 Figure 1: The BFO 2.0 *is\_a* Hierarchy (Version of July 2012)

# Organization of BFO

## Entities

An entity is anything that exists. BFO assumes that entities can be divided into instances (your heart, my laptop) and universals or types (*heart*, *laptop*). On BFO’s usage of ‘instance’ and ‘universals’ see [19, 25].

note(ontology)[BFO does not claim to be a complete coverage of all entities. It seeks only to provide coverage of those entities studied by empirical science together with those entities which affect or are involved in human activities such as data processing and planning – coverage that is sufficiently broad to provide assistance to those engaged in building domain ontologies for purposes of data annotation [17] or representation and reasoning in science, medicine, and many areas of administration and commerce. ]

We leave open the question of how, if at all, BFO would deal with numbers, sets, and other mathematical entities, and with propositions (conceived in the sense of ideal meanings). We foresee two avenues of future development in regard to these and other varieties of entities not currently covered by BFO. First, there will be incremental expansion of BFO in future versions. Second one can draw on supplementary resources at lower levels in the ontology hierarchy. The [Information Artifact Ontology](http://code.google.com/p/information-artifact-ontology/) and the [Ontology for Biomedical Investigations](http://obi-ontology.org/)), both of which are built on BFO, provide the resources to deal with numerical measurement results and with certain other mathematical entities.

## Relations

Entities are linked together in relations at the level of both instances and types [16]. Three groups of relations are distinguished.

1. Instance-level relations

Your heart (instance-level) **continuant\_part\_of** your body **at** *t*Your heart beating (instance-level) **has\_participant** your heart

1. Type-level relations

human heart *continuant\_part­\_of* human body  
 human heart beating process *has\_occurrent\_part* beat profile

1. Instance-type relations

John’s heart **instantiates** *human heart.*

In this document we discuss relations in all three groups; however, BFO 2.0 specifies only the treatment of instance-level relations. Relations between universals are dealt with by using quantifiers over the corresponding instances.

Note that relations of none of these sorts are first-class entities(to see why not, see the discussion of the Bradley regress in [20]). However, there are first-class entities, such as what we can think of as *relational processes* which are ‘relational’ in the sense that they link multiple participants. First-class entities are entities which have counterparts both at the level of instances (John’s act of kissing Mary yesterday) and at the level of universals (*kiss*, *act*, *person*).

## Definitions and Elucidations; Primitives and defined terms

We use terms (such as ‘BFO:*object*’ or ‘Patrick Hayes’) to refer to entities, and relational expressions (such as ‘**has\_participant**’) to assert that relations obtain between such entities.note(ontology)[For both terms and relational expressions in BFO, we distinguish between *primitive* and *defined*. ‘Entity’ is an example of one such primitive term. Primitive terms in a highest-level ontology such as BFO are terms that are so basic to our understanding of reality that there is no way of defining them in a non-circular fashion. For these, therefore, we can provide only elucidations, supplemented by examples and by axioms. ]

a(entity)[Elucidation: An *entity* is anything that exists or has existed or will exist. [001-001]]

as(entity)[Examples: Julius Caesar\, the Second World War\, your body mass index\, Verdi’s *Requiem*

]

### Definitions

Definitions of terms are required to be always of the form:

*A* = Def. *B* which *D*s

where ‘*A*’ is the term to be defined, ‘*B*’ is its immediate parent in the relevant BFO-conformant ontology hierarchy, and ‘*D*’is the differentiating criterion specifying what it is about certain *B*s in virtue of which they are *As*.

Examples (taken from the Foundational Model of Anatomy (FMA) [44]):

Cell = Def. Anatomical structure which has as its boundary the external surface of a maximally connected plasma membrane.

Nucleated cell = Def. Cell which has as its direct part a maximally connected part of protoplasm.

Anatomical boundary entity =Def. Immaterial anatomical entity which is of one less dimension than the anatomical entity it bounds or demarcates from another anatomical entity.

Anatomical surface =Def. Anatomical boundary entity which has two spatial dimensions.

Definitions for relational expressions are statements of necessary and sufficient conditions for the corresponding relation to hold. Examples are provided below, and in [16].

## Avoiding is\_a overloading

In ordinary English the following assertions are equally grammatical:

(a) a human being is a mammal

(b) a professor is a human being

(c) John is a human being

(d) a restaurant registered with the City of Palo Alto is a restaurant subject to Division A18 to the County Of Santa Clara Ordinance Code.

The meaning of ‘is a’ is quite different in each of these four families of cases, and ontologies which do not take account of these differences are guilty of what Guarino has called “‘is a’ overloading” [80]. Here only (a) and (b) are properly to be treated in terms of the *is\_a* relation between universals or types. (c) is an example of instantiation and (d) an example of the relation between two collections of particulars to the effect that one is a sub-collection (subset) of the other.

It is usages (a) and (b) which concern us here – and the reader should note that the English phrase ‘is a’ as used in what follows does not always appear in contexts where it means *is\_a* in the technical sense of ‘is a subtype of’ specified below. (a) and (b) illustrate a distinction between two kinds of *is\_a* relations:

1. between rigid universals, which means: universals which are instantiated by their instances necessarily and which are thus, for each instance, instantiated at all times at which the instance exists. Such universals are sometimes said to capture the nature or essence of their instances;
2. between universals one or both of which is not rigid in this sense, for example (again): a professor is a human being; these examples are dealt with further below.

Note, again, that in our specification of BFO 2.0, universals themselves fall outside our domain of discourse (with the minor exception of the elucidation of *generically dependent continuant*). The mentioned dichotomy between rigid and non-rigid universals should thus be interpreted in such a way that it does not imply any assertion according to which there might be higher-order universals (for instance *rigid universal*) of which first-order universals would somehow be instances.

## Universals and classes

Universals have **instances**, which are in every case particulars (entities located in space and time). Universals also have extensions, which we can think of (set-theoretically) as collections of their instances. Such extensions fall outside the scope of this specification, but it is important for the understanding of BFO that the distinction is recognized. It implies further distinctions not only between universals and their extensions but also between universals and classes in general, including arbitrary classes such as: {the moon, Napoleon, redness}.

Universalsthemselvesare those general entities which need to be recognized in order to formulate both truths of natural science and analogous general assertions concerning (for example) material, social and informational artifacts.

Examples of universals in each of the mentioned realms include:

*Natural:* electron, molecule, cell, mouse, planet, act of perception

*Material artifacts*: vehicle, revolver, pipette, pizza

*Social artifact*: dollar, meter, traffic law, organization, mortgage contract

*Information artifact*: database, ontology, email message, plan specification, experimental protocol.

While universals are most clearly illustrated by considering the general terms – such as ‘electron’ or ‘cell’ – employed by scientific theories in the formulation of general truths [19], universals include also those general entities referred to by general terms employed in domains such as engineering, commerce, administration and intelligence analysis.

It is not up to BFO to decide what universals exist in any given domain; this decision is made by domain experts [19], for example in forming their terminology. In all domains, universals are those general or repeatable entities that correspond to the terms used and reused by persons with domain expertise reused in multiple different sorts of contexts to refer to those multiple different particulars which are the instances of the corresponding universals. axiom(entity)[All entities are either particular or universal.] [19, 22, 23, 89] axiom(entity)[No entity is both a particular and a universal. These statements are provided for documentation purposes, and will be treated formally in a later version of BFO incorporating quantification over universals. Note, in contradistinction to an assumption widely held in certain circles, that the issue of ]whether an entity is a particular or a universal is not a matter of arbitrary choice or of convenience.

In the [Information Artifact Ontology](http://code.google.com/p/information-artifact-ontology/), universals are included among the targets of the IAO:**is\_about** relation. In the specification below, however, we concentrate on particulars and on the instance-level relations that link them together [16]. That is, the categories referred to in this specification are with very few exceptions categories of particulars. A future version of BFO will provide a complementary treatment of universals.

## The monohierarchy principle

BFO rests on a number of heuristic principles that are designed to advance its utility to formal reasoning. These take the form of simple rules – analogous to the rules of the road – that are designed to promote consistency in the making of both domain-neutral and domain-specific choices in ontology construction. [19] One heuristic principle of this kind – expressing what we can think of as a principle of good behavior in the realm of universals – asserts that the asserted taxonomies of types and subtypes in BFO-conformant ontologies should be genuine trees (in the graph-theoretic sense), so that each node in the graph of universals should have at most one asserted *is\_a* parent. (On the use of ‘asserted’ here, see [19].) This principle is of value not only because it supports a simple strategy for the formulation of definitions and thereby helps to prevent certain common kinds of error in ontology construction, but also because it brings technical benefits when ontologies are implemented computationally.

The strategy for ontology building that is recommended by users of BFO involves the creation, first, of asserted *is\_a* hierarchies conforming to BFO, on the basis of a heuristic assumption according to which the realm of universals is organized by the *is\_a* relation into taxonomic hierarchies of more and less general. Each such asserted hierarchy should be constructed as a monohierarchy [19], in which every node has at most one immediate parent. All universals which are the immediate children of any given universal are thereby subject to the monohierarchy principle. However, once a set of what we can think of as normalized monohierarchies has been asserted, then an ontology developer can use reasoning to *infer* multiple inheritance [19, 83].

Examples of general terms that are unproblematically such that they do *not* represent universals include:

* thing that has been measured
* thing that is either a ﬂy or a music box
* organism belonging to the King of Spain
* injury due to piercing, cutting, crushing or pinching due to (by) slide trigger mechanism, scope or other gun part ([ICD-10-CM (2010)](http://en.wikisource.org/wiki/ICD-10-CM_(2010)/CHAPTER_20))

In some areas, for example government administration, we face the need for BFO-conformant ontologies where the divisions created are indeed subject to overlap of their extensions. Thus a *professor* in a medical school may also be a *patient*. Here, too, however, as we shall see, it is still possible to preserve the monohierarchy principal by creating asserted hierarchies of the corresponding *roles*.

## Determinables and determinates

Certain sorts of universals, represented by leaf nodes in a taxonomical hierarchy and typically associated with the possibility of continuous variation along a scale to which real-number measurement values can be assigned, are called ‘determinate universals’ (their ancestor universals are called ‘determinable universals’) [71].

Examples are:   
 *37.0°C temperature*, *1.6 meter length*, *4 kg weight*  
with determinables  
 *temperature*, *length*, *mass*.

Determinable universals are rigid, which means that if a given particular instantiates a given determinable universal at some time, then it instantiates this same determinable universal at all times at which it exists. John’s weight, for example, is an instance of the determinable universals *weight quality* and *quality.* Thus John’s weight is always an instance of these universals whenever it exists. John’s weight is something that we can measure at different times, and when we do so we discover that this qualityinstance instantiates different determinate weight universals at different times, for example (as described in the metric system of units): *4 kg weight, 104 kg weight,* *204 kg weight*, and so on. Note that these weights themselves (these instances of the determinable quality universal, *weight*) are independent of whatever system of units is used in describing them. Thus the determinate universals here referred to would be instantiated – their instances would exist – even in a world in which the metric system of units – or any other system of units – had never existed. All that is required is that there exist bodies of the corresponding weights.

## Specializations

note(entity)[In all areas of empirical inquiry we encounter general terms of two sorts. First are general terms which refer to universals or types:

* animal
* tuberculosis
* surgical procedure
* disease

Second, are general terms used to refer to groups of entities which instantiate a given universal but do not correspond to the extension of any subuniversal of that universal because there is nothing intrinsic to the entities in question by virtue of which they – and only they – are counted as belonging to the given group. Examples are:

* animal purchased by the Emperor
* tuberculosis diagnosed on a Wednesday
* surgical procedure performed on a patient from Stockholm
* person identified as candidate for clinical trial #2056-555
* person who is signatory of Form 656-PPV
* painting by Leonardo da Vinci.

Such terms, which represent what are called ‘specializations’ in [81], may need to be included in application ontologies developed to interoperate with BFO-conformant ontologies. The terms in question may then be defined as children of the corresponding lowest-level universals (for example, in the just-mentioned cases: *animal*, *disease, surgical procedure*, *person*, *painting*). ]

## Role universals

Note(role)[One major family of examples of non-rigid universals involves roles, and ontologies developed for corresponding administrative purposes may consist entirely of representatives of entities of this sort. Thus ‘professor’, for which the usage is defined as follows,

*b* **instance\_of** *professor* **at** *t*

*=*Def. there is some *c*, *c* **instance\_of***professor role* & *c* **inheres\_in** *b* **at** *t.*

denotes a non-rigid universal and so also do ‘nurse’, ‘student’, ‘colonel’, ‘taxpayer’, and so forth. (These terms are all, in the jargon of philosophy, *phase sortals*.) By using role terms in definitions, we can create a BFO conformant treatment of such entities drawing on the fact that, while an instance of *professor* may be simultaneously an instance of *trade union member*, no instance of the type *professor role* is also (at any time) an instance of the type *trade union member role* (any more than any instance of the type *color* is at any time an instance of the type *length*).

If an ontology of employment positions is defined in terms of roles following the above pattern, this enables the ontology to do justice to the fact that individuals instantiate the corresponding universals – *professor*, *sergeant*, *nurse* – only during certain phases in their lives.]

## Universals defined historically

Another important family of universals consists of universals defined by reference to historical conditions, for example: *biological father*, *phosphorylated protein*, *retired major general*, *thing that has been measured*,and so forth. For such terms, in contrast to role universals, there is no simple rule for formulating definitions. In the case of *biological father*, for example, the definition would need to involve reference not only to the fact that each instance is a male organism, but also to the fact that the organism in question was the instigator of a process of fertilization which led to the birth of a second organism.

Why insist on such complex definitions? Why not simply introduce ‘biological father’ as another primitive term referring to a subtype of ‘human being’? The answer turns on the methodology for ontology creation, interoperation and quality control which BFO aims to support, and which is designed to bring it about that (a) the methodology tracks instances in reality in a way that is conformant with our scientific understanding [67], and (b) it does this in a way which helps to ensure that those developing ontologies in neighboring domains do so in a way that preserves consistency and interoperability [19, 78].

## Relations defined for any entity

### The instance\_of relation

The **instance\_of** relation holds between particulars and universals. It comes in two forms, for continuants (*C*, *C*1, …) and occurrents (*P*, *P*1, …) as follows [16]:

*c***instance\_of***C***at***t* means: the particular *continuant* entity *c* **instantiates** the universal *C* **at** *t*

*p***instance\_of***P* means: the particular *occurrent* entity *p* **instantiates** the universal *P.*

Examples are, respectively:

John **instance\_of** *adult* **at** 2012,

this laptop **instance\_of** *laptop* **at** 2012;

2012 **instance\_of** *temporal region*,

John’s birth **instance\_of** *process.*

### The *is\_a* relation

The *is\_a* relation is the subtype or subuniversal relation between universals or types.

*C is\_a C*1means: *C* and *C*1 are continuant universals, and

for all *c*, *t*, if *c***instance\_of***C***at***t*then *c***instance\_of***C*1**at***t*

*P is\_a P*1means: *P* and *P*1 are occurrent universals, and

for all *p*, if *p***instance\_of***P*then *p***instance\_of***P*1

Examples are:

house *is\_a* building

symphony *is\_a* musical work of art;

promenade *is\_a* dance step

promise *is\_a* speech act.

### The exists\_at relation

a(exists\_at)[Elucidation: *b* **exists\_at** *t* means: *b* is an entity which exists at some temporal region *t.* [118-002] ]

a(exists\_at)[Domain: *entity*]

a(exists\_at)[Range: *temporal region*]

The domain of ‘Exists’ includes processes, where *t* is part of the span of the process*.* ‘Temporal region’ includes both temporal instants and temporal intervals.

## The dichotomy of ‘continuant’ and ‘occurrent’

The dichotomy between continuant and occurrent ontologies forms the central organizing axis of the BFO ontology. The BFO view of this dichotomy is inspired by Zemach [60], who distinguishes between

* non-continuant entities, which Zemach calls ‘events’, and which are defined by the fact that they can be sliced along any spatial and temporal dimensions to yield parts (for example the first year of the life of your table; the entire life of your table top – as contrasted with the life of your table legs – and so forth).

An event, for Zemach, is an entity that exists, in its entirety, in the area defined by its spatiotemporal boundaries, and each part of this area contains a *part* of the whole event. There are indefinitely many ways to carve the world into events, some of which are useful and interesting (e.g., for the physicist) and some of which – the vast majority – create hodge-podge collections of no interest whatsoever. [60, pp. 233 f.]

note(continuant)[Continuant entities are entities which can be sliced to yield parts only along the spatial dimension, yielding for example the parts of your table which we call its legs, its top, its nails. ‘My desk stretches from the window to the door. It has spatial parts, and can be sliced (in space) in two. With respect to time, however, a thing is a continuant.’ [60, p. 240]

Thus you, for example, are a continuant, and your arms and legs are parts of you; your childhood, however, is not a part of you; rather, it is a part of that occurrent entity which is your life. Continuants, as a matter of definition, are entities which have no parts along the time axis; in this sense continuants are extended only along one or more of the three spatial dimensions, not however along the temporal dimension. Spatial regions, for BFO, are continuants. Temporal and spatiotemporal regions are occurrents.

BFO generalizes from the above by allowing as continuants not only *things* (such as pencils and people), but also *entities that are dependent on things* (such as qualities and dispositions). And where events, for Zemach, are identified with the entire contents of some given spatiotemporal region, BFO allows that the same spatiotemporal region may be occupied by multiple different processes (as for example your *running* process and your simultaneous process of *getting warmer*). It distinguishes correspondingly between two kinds of processes: plenary processes, on the one hand, and partial processes on the other. Plenary processes satisfy the following principle, that if *p* is a full process, then all processes occurring within the spatiotemporal region occupied by *p* are parts of *p.* For Zemach, as for Quine and (at certain times) Donald Davidson, all processes (alternatively called ‘events’ or ‘occurrents’) are plenary processes, because processes *are* the contents of arbitrary portions of spacetime “no matter how disconnected and gerrymandered” [91].

# Specification

## Relations of parthood

As our starting point in understanding the parthood relation, we take the axioms of Minimal Extensional Mereology as defined by Simons [46, pp. 26-31], assuming, with Simons, the axioms of first order predicate calculus. The axioms (reformulations of SA1-3 and SA6 in Simons’ numbering) are:

**Antisymmetry:** If *x* part of *y*, then if *y* part of *x*, then *x = y.*

**Transitivity:** If *x* part of *y,* and *y* part\_of *z*, then *x* part\_of *z.*

**Weak Supplementation:** If *x* part\_of *y* & not *x* = *y*, then there is some *z* such that (*z* part\_of *y* and *z* has no part in common with *x*).

**Unique Product:** If *x* and *y* have a part in common, then there is some unique *z* such that for all *w* (*w* is part of *z* if and only if (*w* is part of *x* and *w* is part of *y*))*.*

Where Simons takes as primitive the relation of proper parthood, we use here and in the remainder of this document parthood relations that include not only proper parthood but also identity as a special case. The corresponding proper\_part\_ofrelations are then defined in the obvious way as follows:

*x* proper\_part\_of *y* =Def. *x* part\_of *y* & not *x ­= y.*

BFO 2.0 includes two relations of parthood, namely: parthood as it obtains between continuants – called **continuant\_part\_of** – and parthood as it obtains between occurrents – called **occurrent\_part\_of**. Note that Simons’ axioms cited above are stated without reference to time, whereas some of the parthood relations BFO defines are temporally qualified. Therefore the relations and definitions described above are not relations in BFO, rather they serve as a templates used in the elucidation of BFO relations.

### The continuant\_part\_of relation

a(continuant\_part\_of)[Elucidation: *b* **continuant\_part\_of** *c* **at** *t* =Def. *b* is a part of *c* ***at*** *t* & *t* is a temporal region & *b* and *c* are continuants. [002-001]]

a(continuant\_part\_of)[Domain: continuant]

a(continuant\_part\_of)[Range: continuant

(The range for ‘*t*’ (as in all cases throughout this document unless otherwise specified) is: temporal region.)]

as(continuant\_part\_of)[Examples: Mary’s arm **continuant\_part\_of** Mary in the time of her life prior to her operation\; the Northern hemisphere of the planet Earth is a part of the planet Earth at all times at which the planet Earth exists. ]

a(continuant\_part\_of)[Axiom: **continuant\_part\_of** is antisymmetric. [120-001] ]

a(continuant\_part\_of)[Axiom: **continuant\_part\_of** is transitive. [110-001] ]

a(continuant\_part\_of)[Axiom: **continuant\_part\_of** satisfies weak supplementation. [121-001]

What this last axiom means is that:

If *x* **continuant\_part\_of** *y* **at** *t* & not *x* = *y*, then there is some *z* such that (*z* **continuant\_part\_of** *y* **at** *t* & there is no *w*(*w* **continuant\_part\_of** *z* & *w* **continuant\_part\_of** *x* **at** *t*)).

Here *z* is, as it were, some remainder that results when *x* is imagined to have been removed from *y.*]

a(continuant-part-of)[Axiom: **continuant\_part\_of** satisfies unique product. [122-001]

What this axiom means is that:

If *u* **continuant\_part\_of** *x* **at** *t* & *u* **continuant\_part\_of** *y* **at** *t*, then there is some unique *z* such that for all *w* ((*w* **continuant\_part\_of** *z* **at** *t*)if and only if ((*w* **continuant\_part\_of** *x* **at** *t* and *w* **continuant\_part\_of** *y* **at** *t*))).

a(continuant\_part\_of)[Theorem: **continuant\_part\_of** is reflexive (every continuant entity is a **continuant\_part\_of** itself). [111-002] ]

### The occurrent\_part\_of relation

a(occurrent\_part\_of)[Elucidation: *b* **occurrent\_part\_of** *c* =Def. *b* is a part of *c* & *b* and *c* are occurrents. [003-002]]

a(occurrent\_part\_of)[Domain: occurrent]

a(occurrent\_part\_of)[Range: occurrent]

a(occurrent\_part\_of)[Examples: Mary’s 5th birthday **occurrent\_part\_of** Mary’s life\; the first set of the tennis match **occurrent\_part\_of** the tennis match. ]

a(occurrent\_part\_of)[Axiom: **occurrent\_part\_of** is antisymmetric. [123-001] ]

a(occurrent\_part\_of)[Axiom: **occurrent\_part\_of** is transitive. [112-001] ]

a(occurrent\_part\_of)[Axiom: **occurrent\_part\_of** satisfies weak supplementation. [124-001]]

a(occurrent\_part\_of)[Axiom: **occurrent\_part\_of** satisfies unique product. [125-001] ]

a(occurrent\_part\_of)[Theorem: **occurrent\_part\_of** is reflexive (every occurrent entity is an occurrent\_part\_of itself). [113-002] ]

Note that in all of the above every entity is, trivially, note(continuant\_part\_of,occurrent\_part\_of)[a (continuant or occurrent) part of itself. We appreciate that this is counterintuitive for some users, since it implies for example that President Obama is a part of himself. However it brings benefits in simplifying the logical formalism, and it captures an important feature of identity, namely that it is the limit case of mereological inclusion.]

### Further relations defined in terms of parthood

Proper parthood relations can be easily defined, as follows:

For continuants:

a(proper\_continuant\_part\_of)[Definition: *b* **proper\_continuant\_part\_of** *c* **at** *t* =Def. *b* **continuant\_part\_of** *c* **at** *t* & *b* and *c* are not identical. [004-001]]

For occurrents:

a(proper\_occurrent\_part\_of)[Definition: *b* **proper\_occurrent\_part\_of** *c* =Def. *b* **occurrent\_part\_of** *c* & *b* and *c* are not identical. [005-001]]

We can also define inverse relations:

For continuants:

a(has\_continuant\_part)[Definition: *b* **has\_continuant\_part** *c* ***at*** *t* = Def. *c* **continuant\_part\_of** *b* **at** *t.* [006-001]

]

a(has\_proper\_continuant\_part)[Definition: *b* **has\_proper\_continuant\_part** *c* ***at*** *t* = Def. *c* ***proper\_*continuant\_part\_of** *b* **at** *t.* [XXX-001]]

For occurrents:

a(has\_occurrent\_part)[Definition: *b* **has\_occurrent\_part** *c* = Def. *c* **occurrent\_part\_of** *b*. [007-001

]

a(has\_proper\_occurrent\_part)[Definition: *b* **has\_proper\_occurrent\_part** *c* = Def. *c* ***proper\_*occurrent\_part\_of** *b*. [XXX-001]]

## Continuant

The continuant branch of BFO 2.0 incorporates both material and immaterial continuants extended and potentially moving in space, including the spatial regions at which they are located and through which they move, and the associated spatial boundaries. (The approach is similar to the two-leveled approaches developed in [69, 70], though it avoids the reference to ‘quantities of matter’ or ‘bare matter’ which form their starting point.)

a(continuant)[Elucidation: A *continuant* is an entity that persists, endures, or continues to exist through time while maintaining its identity. [008-002]]

Continuants include also spatial regions. note(material entity)[Material entities (continuants) can preserve their identity even while gaining and losing material parts. Continuants are contrasted with occurrents, which unfold themselves in successive **temporal parts** or phases [60]. ]

a(continuant)[Axiom: if *b* is a *continuant* and if, for some *c* and some *t*, *c* **continuant\_part** of*b***at** *t,* then *c* is a *continuant.* [009-002]]

a(continuant)[Axiom: if *b* is a *continuant* and if, for some *t*, *c* **has\_continuant\_part** *b***at** *t,* then *c* is a *continuant.* [126-001]]

If an occurrent **occupies** a certain 2-minute **temporal\_region**, then the occurrent is the sum of two non-overlapping **temporal parts** (see below), each of 1-minute duration. *Continuants* have no **temporal parts**.

Check that we have axioms that continuants have no occurrent parts and that occurrents have no continuant parts.

note(ontology)[BFO’s treatment of continuants and occurrents – as also its treatment of regions, /\*below – thus \*/rests on a dichotomy between space and time, and on the view that there are two perspectives on reality – earlier called the ‘SNAP’ and ‘SPAN’ perspectives, both of which are essential to the non-reductionist representation of reality as we understand it from the best available science [30]. At the same time, however, this dichotomy itself needs to be understood in such a way as to be consistent with those elements of our scientific understanding – including the physics of relativity – with which it might seem to stand in conflict. It must be consistent, above all, with what we know from physics about the entanglements of space and time both with each other, and with matter and causality. The starting point for our approach in this connection is well-captured by Simons:

the evidence that relativity theory forces us to abandon the ontology of continuants and events is slight and circumstantial. It is true that Minkowski diagrams represent time as simply another dimension along with the spatial ones, but we cannot argue from a diagram, which is only a convenient form of representation. A closer examination of the concepts and principles of relativity shows that they rest squarely on the ontology of things and events. A *world-line* is a sum of events, all of which involve a single *material body*; any two events on the same world-line are *genidentical.* That which cannot be accelerated up to or beyond the speed of light is something with a non-zero mass. But only a continuant can have a mass. In like fashion, the measuring rods and clocks of special relativity, which travel round from place to place, are as assuredly continuants as the emission and absorption of light signals are events. Nor does relativity entail that large continuants have temporal as well as spatial parts. It simply means that the questions as to which parts large continuants have at a given time have no absolute answer, but depend on fixing which events (such as gains and losses of parts) occur simultaneously. Whether body of gas A detaches itself from a large star before, after, or simultaneously with the falling of body of gas B into the star, may depend on the inertial frame chosen. ([46], pp. 126 f.; compare also [55, pp. 128-32])

### Excursus on frames

The four dimensions of the spacetime continuum are not homogeneous. Rather there is one time-like and three space-like dimensions. This heterogeneity is sufficient, for the purposes of BFO, to justify our division of reality in a way that distinguishes spatial and temporal regions. In a future version, however, we will need to do justice to the fact that there are multiple ways of dividing up the spacetime continuum into spatial and temporal regions, corresponding to multiple coordinate frames that might be used by different observers. We believe that current users of BFO are not dealing with the sorts of physical data for which frame dependence is an issue, and the frames that they are using can be calibrated, where necessary, by using the simple mappings we use when for example translating between Eastern Standard Time and Greenwich Mean Time). We note, in anticipation of steps to be taken in the future, that spatiotemporal regions are frame-independent, and also that very many of the assertions formulated using BFO terms are themselves frame-independent; thus for example relations of parthood between material entities are *intrinsic*, in the sense that if *b* is part of *c* at some time in one frame, then *b* is part of *c* at some time in all frames. ]

## Relation of specific dependence

Specific dependence is a relation (henceforth: **s-depends on**) that obtains between one entity and another when the first entity cannot exist unless the second entity exists also. This relation can be either one-sided, in the sense that *b* **s-depends\_on** *c*, but not (*c* **s-depends\_on** *b*), or mutual where *b* and *c* **s-depend\_on** each other. There are cases where a single entity is s-dependent on multiple other entities in either or both senses of ‘s-dependence’. In a future version of BFO, further varieties of dependence will be defined, including **boundary dependence**which holds between entities of lower dimension and the higher-dimensional entities which they bound. On the distinction between boundary dependence and specific dependence, see [90].

a(s-depends on)[Elucidation: To say that *b* **s-depends\_on** *c* **at** *t* is to say that

*b* and *c* do not share common parts

& *b* is of its nature such that it cannot exist unless *c* exists

& *b* is not a boundary of *c* and *b* is not a site of which *c* is the host [64]. [012-002]]

as(s-depends on)[Domain: *specifically dependent continuant*\; *process*; *process boundary*]

Range:

range(s-depends on)[for one-sided s-dependence: *independent continuant*;]

range(s-depends on)[for mutual s-dependence: *dependent continuant*\; *process*]

as(s-depends on)[Examples: A pain **s-depends\_on** the organism that is experiencing the pain\, a shape **s-depends\_on** the shaped object\, a gait **s-depends\_on** the walking object. (All at some specific time.)]

Note that the first clause in the above ensures that parts of wholes (for example your heart, which is a part of you) do not **s-depend on** the wholes of which they are parts.

ADD AXIOM s-dependence is transitive [if not included already below]

If *b* **s-depends\_on** *c***at** *t*, thenwe can also say that *b*’sexistencerequires (necessitates) the existence of *c* [66], or that *b* is of necessity associated with some *c* *because* *b* is an instance of a certain universal*.*

*FORMULATE AS AXIOM:* The s-dependence of an entity *b* on another entity *c* holds for the duration of the existence of *b*.

Thus for continuants *b* and *c*, if *c* is such that *b* **s-depends\_on** *c* **at** *t*, then if *c* ceases to exist so also does *b*. The ceasing to exist of *b* occurs as a matter of necessity (it is in a sense immediate and automatic). Thus **s-dependence** is different from the sort of dependence which is involved, for instance, when we assert that an organism is dependent on food or shelter; or that a child is dependent on its mother. Your body is dependent on molecules of oxygen for its life, not however for its existence. Similarly, **s-dependence** is different from the sort of dependence that is involved when we assert that every object requires, at any given time *t*, some spatial region at which it is **located** at that time. (We use ‘**occupies\_spatial\_region**’ for dependence of this sort.)

Occurrents, too, may stand in s-dependence relations to independent continuants. **S-dependence** obtains between every process and its independent continuant participants in the sense that, as a matter of necessity, this process could not have existed unless these or those independent continuant participants existed also. A *process* may have a succession of such participants at different phases of its unfolding. Thus there may be different players on the field at different times during the course of a football game; then some temporal parts of the game will then **s-depend\_on** only some of the players.] Thus if a football match *m* consists of two halves, *m*1and *m*2, in which a player *j* is on the field during the first but not during the second half. Then the whole match *m* is dependent on *j*, and the first half of the match *m*1 is dependent on *j*, but the second half of the match *m*2 – that **temporal part** of the whole process – is not dependent on *j.* (He participates in the whole match, but not in the second half.)

editor-note(specifically depends on)[**S-dependence** is what, in the literature, is referred to as ‘existential dependence’ [20, 46, 65, 87], since it has to do with the parasitism among entities *for their existence*]; there are other types of dependence defined in terms of **specific dependence**, including **generic dependence** which is dealt with below. Other types of dependence not addressed in BFO 2.0 include:

* frame dependence (of spatial and temporal regions on spatiotemporal regions)
* dependence for origin (e.g. an artifact such as a spark plug depends on human designers and engineers for the *origin* of its existence, not however for its *continued existence*; you depend similarly on your parents for your origin; the boundary of Iraq depended on certain decisions made by the British and French diplomats [Sir Mark Sykes](http://en.wikipedia.org/wiki/Mark_Sykes) and [François Georges-Picot](http://en.wikipedia.org/wiki/Fran%C3%A7ois_Georges-Picot) in 1916; it does not, however, depend on Sykes and Picot for its continued existence.

a(s-depends on)[Theorem: an *entity* does not **s-depend\_on** any of its (continuant or occurrent) partsor on anything it is partof. [013-002]]

This follows trivially from the definition.

As we shall see when we consider the parts of *qualities* such as color and tone below, the parts of a dependent entity may mutually **s-depend\_on** each other. This idea has not hitherto been explicitly recognized in BFO, but it is documented at length in the literature on specific dependence [1, 2, 3, 6, 20, 46].

An *s-dependent continuant entity* cannot migrate from one independent continuant bearer to another.

as(s-depends on)[Axiom: If *occurrent b* **s-depends\_on** some *independent continuant* *c* **at** *t*, then *b* **s-depends\_on** *c* at every time at which *b* exists. [015-002]

Axiom: If *b* **s-depends\_on** *c* **at** *t* and *b* is a *continuant*, then *b* **s-depends\_on** *c* at every time at which *b* exists. [016-001]

Axiom: If *b* is a continuant and *b* **s-depends\_on** *c***at** *t*, then  *b* exists **at** *t*. [127-001]

Axiom: If *b* is a continuant and *b* **s-depends\_on** *c***at** *t*, then *c* exists **at** *t*. [128-001]

Axiom: If *b* is an occurrent and *c* is a continuant and *b* **s-depends\_on** *c* **at** *t,* then *c* exists at some time during the temporal region spanned by *b.* [129-001]

Axiom: If *b* is an occurrent and *c* is an occurrent and *b* **s-depends\_on** *c* **at** *t,* then *c* exists **at** t *.* [130-001]]

The entities that **s-depend\_on** somethinginclude:

* *specifically and generically dependent continuants*, which **s-depend** in every case **on** one or more *independent continuants* which are their bearers, and which may in addition stand in **s-depends\_on** relations among themselves;
* *occurrents*, which **s-depend** in every case **on** one or more *independent continuants* which **participate** in them, and which may in addition stand in **s-depends\_on** relationsto other dependent entities, including *qualities*, *dispositions*, and to other *occurrents* (see [46, chapter 8; 20, 22] and the discussion of *process profiles*, below).

### Types of s-dependence

Examples of **one-sided s-dependence** of a *dependent continuant* on an *independent continuant*:

* example(s-depends on)[one-sided s-dependence of a dependent continuant on an independent continuant: this **instance** of *headache* **s-depends\_on** this *head*]
* example(s-depends on)[one-sided s-dependence of a dependent continuant on an independent continuant: this **instance** of *temperature* **s-depends\_on** this organism]

Example of **one-sided s-dependence** of a *process* on something:

* example(s-depends on)[one-sided s-dependence of a process on something: this **instance** of *seeing* (a relational process) **s-depends\_on** this organism and on this seen entity, which may be an *occurrent* or a *continuant*]
* example(s-depends on)[one-sided s-dependence of a process on something: this *process* of cell death **s-depends\_on** this cell]

Examples of **mutual s-dependence** between *dependent continuants*:

* example(s-depends on)[mutual s-dependence between *dependent continuants*: the two-sided mutual **s-dependence** of the *roles* of husband and wife [20]]
* example(s-depends on)[mutual s-dependence between *dependent continuants*: the three-sided mutual **s-dependence** of the hue, saturation and brightness of a color [45]]

Note that mutually dependent entities are in every case also one-sidedly dependent on some relevant bearers.

Examples of **one-sided s-dependence** of an *occurrent* on an *independent continuant*:

* example(s-depends on)[the one-sided dependence of an occurrent on an independent continuant: this handwave on this hand]
* example(s-depends on)[the one-sided dependence of an occurrent on an independent continuant: this football match on these players, ground, and ball]

Examples of **one-sided s-dependence** of one *occurrent* on multiple *independent continuants*:

* example(s-depends on)[one-sided s-dependence of one occurrent on multiple independent continuants: this relational *process* of hitting this ball with this cricket bat]
* example(s-depends on)[one-sided s-dependence of one occurrent on multiple independent continuants:this relational *process* of paying this coin to this merchant in exchange for this bag of figs]

Examples of **one-sided s-dependence** of one *occurrent* on another

* example(s-depends on)[one-sided s-dependence of one occurrent on another: this *process* of answering this question is dependent on a prior *process* of asking the question]
* example(s-depends on)[one-sided s-dependence of one occurrent on another: this *process* of obeying this command is dependent on this prior *process* of issuing the command]

Examples of **mutual s-dependence** between *occurrents*:

* example(s-depends on)[reciprocal s-dependence between occurrents: in a game of chess this process of playing with the white pieces is mutually dependent on this process of playing with the black pieces]
* example(s-depends on)[reciprocal s-dependence between occurrents: this process of buying is mutually dependent on this associated process of selling]
* example(s-depends on)[reciprocal s-dependence between occurrents: this process of increasing the volume of this portion of gas while temperature remains constant is mutually dependent on this associated process of decreasing the pressure exerted by the gas]

note(s-depends on)[An entity – for example an act of communication or a game of football – can **s-depend\_on** more than one entity. Complex phenomena for example in the psychological and social realms (such as inferring, commanding and requesting) or in the realm of multi-organismal biological processes (such as infection and resistance), will involve multiple families of dependence relations, involving both continuants and occurrents [1, 4, 28]].

As the examples under the heading of one-sided **s-dependence** among *occurrents* show, note(s-depends on)[the relation of **s-depends\_on** does not in every case require simultaneous existence of its relata. Note the difference between such cases and the cases of continuant universals defined historically: the act of answering depends existentially on the prior act of questioning; the human being who was baptized or who answered a question does not himself depend existentially on the prior act of baptism or answering. He would still exist even if these acts had never taken place. /\* A protein molecule that becomes phosphorylated existed before phosphorylation occurs and it might still have existed even though phosphorylation never occurred. (In a later version of BFO we will address the issue of this dependence of the phosphorylated molecule on the process of phosphorylation.) \*/]

## Independent continuant

a(independent continuant)[Definition: *b* is an *independent continuant* = Def. *b* is a *continuant* which is such that there is no *c* and no *t* such that *b* **s-depends\_on** *c* **at** *t.* [017-002]]

as(independent continuant)[Examples: an atom\, a molecule\, an organism\, a heart\, a chair\, the bottom right portion of a human torso\, a leg\; the interior of your mouth\; a spatial region\; an orchestra\; Utah\; the United States Supreme Court. ]

a(independent continuant)[Axiom: For every *independent continuant b* and time *t* during the region of time spanned by *b*’s life, there is at least one *entity* which **s-depends\_on** *b* during *t*. [018-003]

We say ‘during *t*’ since there may be regions *t* such that no single entity **s-depends\_on** *b* exactly in the region *t.* ]

Examples of entities that **s-depend\_on** *independent continuants* are: qualities, dispositions, processes.

## Material entity

a(material entity)[Elucidation: A *material entity* is an *independent continuant* that has some portion of matter as proper or improper **continuant** **part.** [019-002]]

as(material entity)[Examples: a photon\, a human being\, the undetached arm of a human being\, an aggregate of human beings. ]

note(material entity)[‘Portion of matter’ is intended to encompass both mass and energy (we will address the ontological treatment of portions of energy in a later version of BFO). A portion of matter is anything that includes elementary particles among its proper or improper parts: quarks and leptons, including electrons, as the smallest particles thus far discovered; baryons (including protons and neutrons) at a higher level of granularity; atoms and molecules at still higher levels, forming the cells, organs, organisms and other material entities studied by biologists, the portions of rock studied by geologists, the fossils studied by paleontologists, and so on. ]

Every *material entity* at any given time is localized in space at that time. Every *material entity* can move in space.

a(material entity)[Axiom: Every *entity* which has a *material entity* as **continuant part** is a *material entity*. [020-002]]

a(continuant)[Axiom: if *b* is a *material entity*, then there is some **temporal interval** (referred to below as a *one-dimensional temporal region*) during which *b* exists. [011-002]]

Note: *Material entities* may exist (persist, endure) for very short periods of time (as for example in the case of an atom of a highly unstable isotope).

a(material entity)[Theorem: Every *entity* of which a *material entity* is **continuant part** is also a *material entity.* [021-002]]

*Material entities* are three-dimensional entities (entities extended in three spatial dimensions), as contrasted with the *processes* in which they participate, which are four-dimensional entities (entities extended also along the dimension of time).

According to the FMA, *material entities* may have *immaterial entities* as parts – including the *entities* identified below as *sites*; for example the interior (or ‘lumen’) of your small intestine is a part of your body. BFO 2.0 embodies a decision to follow the FMA here. (Note, however, that we do not follow follow the FMA in insisting on the rule that the parthood relation exists only between entities of the same number of dimensions; a point, for BFO, is part of a line; not however for the FMA [88].) Thus we allow **continuant\_part\_of** to include material wholes with immaterial parts, and recommend the use of the more specific relation of **material\_part\_of** where such immaterial parts need to be ruled out. ]

#### Subtypes of material entity

In what follows we define three children of ‘material entity’ – namely ‘object’, ‘object aggregate’; and ‘fiat object part’. Those using BFO for molecular biology and related matters may wish to use ‘material entity’ solely, and not concern themselves with these subdivisions. Those using BFO to deal with entities at higher levels of granularity – for example organisms, populations, inventorized collections, organizations, institutions, will require the distinction between *object* and *object aggregate*. Those using BFO to deal with what the FMA calls regional parts – for example the wall of the cervical, thoracic and abdominal parts of the esophagus, respectively [44] – will need to distinguish between *object* and *fiat object part*.

Some might argue that the mentioned threefold distinction could be recreated for each corresponding domain ontology according to need, for example the distinction between ‘organism’, ‘population of organisms’, and ‘regional part of organism’ in an upper level ontology for biology. Since this would mean that multiple different domain ontologies would be called upon, in effect, to reinvent the same wheel over and over again, we provide the corresponding tripartite distinction within BFO in what we hope is a suitably robust framework.

### Object

note(object)[BFO rests on the presupposition that at multiple micro-, meso- and macroscopic scales reality exhibits certain stable, spatially separated or separable material units, combined or combinable into aggregates of various sorts (for example organisms into what are called ‘populations’). Such units play a central role in almost all domains of natural science from particle physics to cosmology. Many scientific laws govern the units in question, employing general terms (such as ‘cell’ or ‘planet’) referring to the types and subtypes of units, and also to the types and subtypes of processes (such as *cell division* or *orbit*) through which such units develop and interact. The division of reality into such *natural units* is at the heart of biological science, as also is the fact that these units may form higher-level units (as cells form multicellular organisms) and that they may also form *aggregates* of units, for example as organisms form families, herds, breeds, species, and so on.

At the same time, the division of certain portions of reality into *engineered units* (manufactured artifacts) is the basis of modern industrial technology, which rests on the distributed mass production of engineered parts through division of labor and on their assembly into larger, compound units such as cars and laptops. The division of portions of reality into units is one starting point for the phenomenon of *counting*.]

Examples of units of special importance for the purposes of natural science include: example(object)[atom\, molecule\, organelle\, cell\, organism\, grain of sand\, planet\, star]. These *material entities* are candidate examples of what are called note(object)[‘*objects*’ /\*in BFO 2.0. Such units \*/are sometimes referred to as ‘grains’ [74], and are associated with specific levels of granularity in what is seen as a layered structure of reality, with units at lower and more fine-grained levels seen as being combined as parts into grains at higher, coarse-grained levels. Our proposals here are consistent with but are formulated independently of such granularity considerations, which will be addressed in a later version of BFO.]

In the following we document a set of conditions to be used when deciding whether entities of a given type should be represented as *objects* in the BFO sense. It is provided as precursor to a formal theory (of qualitative mereotopology [5, 22, 36, 37, 39]) of BFO:*object*.

#### Causal unity

We consider three candidate examples of objects in the BFO sense, namely:

1. organisms, cells and potentially also biological entities of certain other sorts, including organs
2. portions of solid matter such as rocks and lumps of iron
3. engineered artifacts such as watches and cars.

Material entities under all of these headings are all *causally relatively isolated entities* in Ingarden’s sense [47, 13]. This means that they are both *structured* through a certain type of causal unity and sometimes *maximal* relative to this type of causal unity.

We first characterize causal unity in general; we then distinguish three types of causal unity corresponding to the three candidate families of BFO:*objects* (cells and organisms; solid portions of matter; machines and other engineered artifacts) listed above. We then describe what it is for an entity to be maximal relative to one or other of these types, and formulate in these terms an elucidation of ‘object’. Where smaller units form the low-level parts of such causally structured units, such units will typically survive the loss of causal unity, for example as occurs during phase transitions from solid to liquid to gas.

note(object)[To say that *b* is *causally unified* means:

*b* is a material entity which is such that its material parts are tied together in such a way that, in environments typical for *entities* of the type in question,

if *c,* a **continuant part** **of** *b* that is in the interior of *b* ***at*** *t,* islarger than a certain threshold size (which will be determined differently from case to case, depending on factors such as porosity of external cover) and is moved in space to be **at** t *′* ata location on the exterior of the spatial region that had been occupied by *b* ***at*** *t,* then *either b*’s other parts will be moved in coordinated fashion *or b* will be damaged (be affected, for example, by breakage or tearing) in the interval between *t* and *t′*.

causal changes in one part of *b* can have consequences for other parts of *b* without the mediation of any entity that lies on the exterior of *b.*

Material entities with no proper material parts would satisfy these conditions trivially.

Candidate examples of types of causal unity for material entities of more complex sorts are as follows (this is not intended to be an exhaustive list):

##### CU1: Causal unity via physical covering

Here the parts in the interior of the unified entity are combined together causally through a common membrane or other physical covering. The latter points outwards toward and may serve a protective function in relation to what lies on the exterior of the entity [13, 47].

Note that the physical covering may have holes (for example pores in your skin, shafts penetrating the planet’s outer crust, sockets where conduits to other entities are connected allowing transport of liquids or gases). The physical covering is nonetheless *connected* in the sense that (a) between every two areas on its surface a continuous path can be traced which does not leave this surface, and also (b) the covering serves as a barrier preventing entities above a certain size threshold from entering from the outside or escaping from the inside [85, 77].

Some organs in the interior of complex organisms manifest a causal unity of this type. Organs can survive detachment from their surroundings, for example in the case of transplant, with their membranes intact. The FMA [44] defines ‘organ’ in this spirit as follows:

An anatomical structure which has as its direct parts portions of two or more types of tissue or two or more types of cardinal organ part which constitute a maximally connected anatomical structure demarcated predominantly by a bona fide anatomical surface. Examples: femur, biceps, liver, heart, skin, tracheobronchial tree, ovary.

##### CU2: Causal unity via internal physical forces

Here the material parts of a material entity are combined together causally by sufficiently strong physical forces, for example, by fundamental forces of strong and weak interaction, by covalent or ionic bonds, by metallic bonding, or more generally by forces of a type which makes the overall sum of forces strong enough to act in such a way as to hold the object together relative to the strength of attractive or destructive forces in its ordinary environmental neighborhood. (Few solid portions of matter in our everyday environment would survive very long on the face of a neutron star, but luckily such cases are not manifested in our ordinary environment.) In the case of larger portions of matter the constituent atoms are tightly bound to each other in a geometric lattice, either regularly (as in the case of portions of metal) or irregularly (as in an amorphous solid such as a portion of glass). Examples: *atoms*, *molecules*, *grains of sand*, *lumps of iron.*

##### CU3: Causal unity via engineered assembly of components

Here the material parts of a material entity are combined together via mechanical assemblies joined for example through screws or other fasteners. The assemblies often involve parts that are reciprocally engineered to fit together, as in the case of dovetail joints, balls and bearings, nuts and bolts. A causal unity of this sort can be interrupted for a time, as when a watch is disassembled for repair, and then recreated in its original state. The material parts of an automobile, including the moving parts, constitute an object because of their relative rigidity: while these parts may move with respect to each other, a given gear cannot move e.g., 10 ft., while the other parts do not. To allow for such movement, the automobile includes also immaterial parts, such as the interior of its engine cylinders (the space in which a piston travels) or the space occupied by driver and passengers.

We can now describe what it means for a material entity to be *maximal* relative to one or other of these three types of causal unity, and thereby introduce the BFO primitive *object*, as follows

To say that *b* is *maximal* relative to some criterion of causal unity CU*n* means:

*b* is causally unified relative to CU*n* ***at*** *t*

&if for some *t* and *c* (*b* **continuant\_part\_of** *c* **at** *t*& *c* is causally unified relative to the same CU*n*) then *b* and *c* are identical.

For example:

* relative to the causal unity criterion CU1: a cell or organism is maximal; your lower torso falls short of maximality; a pair of cells exceeds maximality.
* relative to the causal unity criterion CU2: a continuous dumbbell-shaped lump of iron is maximal; the connecting portion falls short of maximality; a pair of such dumbbell-shaped lumps exceeds maximality, and so is not an object.
* relative to the causal unity criterion CU3: an armored vehicle is maximal; the portions of armor of an armored vehicle falls short of maximality; a pair of armored vehicles exceeds maximality.]

#### Elucidation of bfo:object

We cannot define ‘object’ in BFO simply by asserting that an entity is an object if and only if it is maximal relative to some causal unity criterion. This is because objects under all three of the headings around which our discussions are focused may have other, smaller objects as parts. A spark plug is an object according to criterion CU3; when inserted into a car to replace a defective spark plug, then it remains an object, but ceases to be maximal. Importantly, however, the spark plug as installed still instantiates a universal many instances of which aremaximal. This suggests that we elucidate ‘object’ as follows:

a(object)[Elucidation: *b* is an *object* means: *b* is a *material entity* which

manifests causal unity of one or other of the types CU*n* listed above

& is of a type (a material universal) instances of which are maximalrelative to this criterion of causal unity. [024-001]]

#### Objects can be joined to other objects

note(object)[Each *object* is such that there are *entities* of which we can assert unproblematically that they lie in its interior, and other *entities* of which we can assert unproblematically that they lie in its exterior. This may not be so for *entities* lying at or near the boundary between the interior and exterior. This means that two objects – for example the two cells depicted in Figure 2 – may be such that there are material entities crossing their boundaries which belong determinately to neither cell. Something similar obtains in certain cases of conjoined twins (see below).]



Figure : [An example of cell adhesion](http://php.med.unsw.edu.au/cellbiology/index.php?title=File:Cell_adhesion_summary.png)

Some instances of any given BFO:*object* universal – for example *cell* or *organism* or *laptop –* are separated by spatial gaps from other instances of this same *object* universal. The spatial gaps may be filled by a medium, for example of air or water. (There are cells not attached to other cells; there are spatially separated organisms, such as you and me. Peas in a pea pod are initially attached to the interior of the pea pod covering. Sperm initially float freely; some sperm become fused with oocytes through a membrane fusion process.)

#### Objects may include other objects as parts

They may do this, for example,

* by containing atoms and molecules as parts;
* by containing cells as parts, for instance the blood cells in your body;
* by containing objects which are bonded to other objects of the same type in such a way that they cannot (for the relevant period of time) move separately, as in the case of the cells in your epithelium or the atoms in a molecule;
* by containing objects which are connected by conduits or tracts which may themselves have covering membranes*.*

Clearly, *objects* may also include *object aggregates* as parts. Some *objects*,as we saw, may also have immaterial parts (the lumen of your gut, the immaterial volume (site) between the face and crystal through which the hands of a mechanical watch move) [34].

#### Conjoined twins

Some objects may change type from one time to the next (a fetus becomes a baby, which in turn becomes a child). Conjoined twins may be successfully separated. Two boats may be combined to form a single multi-hulled boat.

Whether each one of a pair of conjoined twins is or is not an object is not a trivial question, and there are different answers to the question as to what the proper ontological treatment ought to be for different sorts of cases. In cases where twins do not share vital organs an identification of each one of the pair as an object will yield a workable solution, but this need not be so for other cases. Certainly, the maximal CU1-causally unified material entity in such cases is the whole which they together form; accepting each twin as an object even prior to separation, however – thus as an instance of the material universal *human being* – is consistent with our elucidation of BFO:*object*.

### Object aggregate

*Object aggregate* is to be treated as a close analogue of *set of objects,* in the mathematician’s sense; thus an object aggregate has no parts other than the objects that are its members. In this document we concentrate on the use of ‘aggregate’ as it appears in the term ‘object aggregate’. However, ‘aggregate’ should be understood as being generalizable to all continuant BFO categories. Thus for each BFO category *X*, the user of BFO has at their disposal also the category *aggregate of X* [51].

First we define

a(member\_part\_of)[Definition: *b* **member\_part\_of** *c* **at** *t* =Def. *b* is an *object*

& there is **at** *t* a mutually exhaus tive and pairwise disjoint partition of *c* into *objects* *x*1, …, *x*n (for some *n* >1) with *b* = *xi*  for some 1 ≤ *i* ≤ *n.* [026-004]]

a(member\_part\_of)[Domain: *object*]

a(member\_part\_of)[Range: *object aggregate*]

a(member\_part\_of)[Theorem: If *b* **member\_part\_of** *c* **at** *t* then *b* **continuant\_part\_of** *c* **at** *t.* [104-001] ]

as(member\_part\_of)[Examples: each tree in a forest is a **member\_part** of the forest\; each piece in a chess set is a member part of the chess set; each Beatle in the collection called *The Beatles* is a member part of *The Beatles.* ]

a(object aggregate)[Elucidation: *b* is an *object aggregate* means: *b* is a *material entity* consisting, at any time *t* at which *b* exists, exactly of a plurality of *objects* as **member\_parts at** *t*. [025-005]]

Thus axiom(object aggregate)[if b is an *object aggregate*, then if *b* exists **at** t, there are *objects o*1, …,*o*n **at** t such that:

for all *x* (*x* **continuant\_part\_of** *b* **at** *t* iff *x* overlaps some *oi***at** *t*) ]

Here ‘overlaps’ is used in the standard way to mean: ‘shares a common part with’.

definition(object-aggregate)[An entity *b* is an object aggregate **at** *t* if and only if there is a mutually exhaustive and pairwise disjoint partition of *b* into objects **at** *t* [63]. ]

as(object aggregate)[Examples: a symphony orchestra\, the aggregate of bearings in a constant velocity axle joint\, the nitrogen atoms in the atmosphere\, a collection of cells in a blood biobank. ]

The **member parts** of an *object aggregate* are the proximal parts of the aggregate – those parts that determine the aggregate as an aggregate (sometimes referred to as ‘grains’ or ‘granular parts’ [74]).

Different sorts of examples of object aggregates satisfy further conditions. For example, example(object aggregate)[an organization is an aggregate whose **member parts** have roles of specific types (for example in a jazz band, a chess club, a football team)\; a swarm of bees is an aggregate of members who are linked together through operations of their motor and visual systems]; and so on.

Object aggregates may be example(object aggregate)[defined through physical attachment: /\*(\*/the aggregate of atoms in a lump of granite]), or example(object aggregate)[defined through physical containment: /\*(\*/the aggregate of molecules of carbon dioxide in a sealed container\, the aggregate of blood cells in your body]). Object aggregates may be example(object aggregate)[defined by fiat:/\*, for example in the case of \*/the aggregate of members of an organization]; or example(object aggregate)[defined via attributive delimitations such as: the patients in this hospital\, the residents of Palo Alto\, your collection of Meissen ceramic plates.]

[76] provides a formal treatment of aggregates (there called ‘collections’) that is broadly consistent with the above except that it assumes that membership in a collection is fixed over time. However, as is true for many material entities, note(object aggregate)[object aggregates may gain and lose parts while remaining numerically identical (one and the same individual) over time. This holds both for aggregates whose membership is determined naturally (the aggregate of cells in your body) and aggregates determined by fiat (a baseball team, a congressional committee).]

### Fiat object part

Clearly not all material entities form separated or separable natural units in the way described above (see [12]), and so there is – in dealing with extremities demarcated within a body, of mountains demarcated within mountain ranges, and so forth – a need for some way to do justice to material entities distinguished by fiat within larger object wholes, entities here called ‘fiat object parts’.



Figure 3: [Mount Everest from space](http://www.webstuffscan.com/wp-content/uploads/2007/01/mount%20everest%20from%20space.jpg)

a(fiat object part)[Elucidation: *b* is a *fiat object part* = Def. *b* is a *material entity* which is such that

for all times *t*,if *b* exists **at** *t*then

there is some object *c* such that *b* **proper continuant\_part** of *c* **at** *t* and *c* is demarcated from the remainder of *c* by a two-dimensional continuant fiat boundary*.* [027-004]]

as(fiat object part)[Examples: the upper and lower lobes of the left lung\, the dorsal and ventral surfaces of the body\, the Western hemisphere of the Earth\, the FMA:*regional parts* of an intact human body. ]

Since *fiat object parts* are *material entities*, they are also extended in space in three dimensions (in contrast to *continuant fiat boundaries*, introduced below).

Fiat object parts are contrasted with those object parts which are themselves objects – for example those cells which is a part of a multi-cellular organism – and thus are marked by *physical discontinuities* of the sort illustrated, for example, when two people are separated by a 10 meter gap [8, 9] or two cells within your blood screen are separated by a portion of plasma. (We reserve the proper treatment of such physical discontinuities for a later version of BFO.) note(fiat object part)[Many examples of fiat object parts are associated with theoretically drawn divisions], for example example(fiat object part)[the division of the brain into regions\, the division of the planet into hemispheres\, or with divisions drawn by cognitive subjects for practical reasons, such as the division of a cake (before slicing) into (what will become) slices (and thus **member parts** of an *object aggregate*). However, this does not mean that *fiat object parts* are dependent for their existence on divisions or delineations effected by cognitive subjects. If, for example, it is correct to conceive geological layers of the Earth as fiat object parts of the Earth, then even though these layers were first delineated in recent times, they still existed long before such delineation and what holds of these layers (for example that the oldest layers are also the lowest layers) did not begin to hold because of our acts of delineation.

Where fiat boundaries were described e.g. in [8] as boundaries which exist only in virtue of the different sorts of demarcations effected cognitively by human beings, it is clear that once we have recognized the universal of fiat boundaries, then we can see that there are other instances of this universal, which are not cognitively dependent, for instance the fiat boundary separating the territories of pre-human animals such as clownfish or lizards.

#### Treatment of material entity in BFO

Examples viewed by some as problematic cases for the trichotomy of *fiat object part*, *object*, and *object aggregate* include:

a mussel on (and attached to) a rock, a slime mold, a pizza, a cloud, a galaxy, a railway train with engine and multiple carriages, [a clonal stand of quaking aspen](http://scienceblogs.com/evolvingthoughts/2007/08/what_is_an_individual.php), a bacterial community (biofilm), a broken femur.

Note that, as Aristotle already clearly recognized, such problematic cases – which lie at or near the penumbra of instances defined by the categories in question – need not invalidate the categorial distinctions in relation to which they are problematic. The existence of grey objects does not prove that there are not objects which are black and objects which are white; the existence of mules does not prove that there are not objects which are donkeys and objects which are horses. It does, however, show that the examples in question need to be addressed carefully in order to show how they can be fitted into the proposed scheme, for example by recognizing additional subdivisions [29]. But where users of BFO 2.0 need to annotate data pertaining to such problematic cases, then they may in every case use BFO:*material entity* in formulating the corresponding annotations. In the case of the following examples of *material entity* (thus of *continuants*):

example(material entity)[an epidemic\, a hurricane\, a tornado\, a forest fire\, a flame\, a puff of smoke\, a wind-caused ocean wave\.]

We plan to provide further analyses in the course of developing the next version of BFO. What makes all of these entities continuants is that they can move and change their shape and other qualities with time while preserving their identity. Some of them are even baptized with proper names.

Already it is clear that BFO or its conformant domain-ontologies will in due course need to recognize also other sub-universals of *material entity*, in addition to *object, object aggregate* and *fiat object part* – for instance: *aggregate of fiat object parts* [29, 82]. Thus the treatment of *material entity* in BFO 2.0 should not be associated with any closure axiom pertaining to the three distinguished categories, in other words it should not be associated with any claim to exhaustivity.

Our strategy for dealing with such sub-universals is to create a central repository where users of BFO can create BFO-conformant extensions (extending BFO in ways that meet the criterion that they are formal- rather than domain-ontological). The terms in this repository can then be adopted by others according to need, and incorporated into BFO if adopted by multiple communities of users.

## Immaterial entity

*Immaterial entities* are independent continuants which contain no material entities as parts. The roots of BFO’s treatment of such entities lie in the application of theories of qualitative spatial reasoning to the geospatial world, for example as outlined in [49, 69], in the treatment of holes by Casati and Varzi [48], in the treatment of niches by Smith and Varzi [7, 10], and in the treatment of cavities in the FMA [43, 44, 34, 35].

Rosse and Mejino provide the following rationale for including terms for surfaces, lines, and points in the FMA:

Although anatomical texts and medical terminologies with an anatomical content deal only superﬁcially, if at all, with anatomical surfaces, lines, and points, it is nevertheless necessary to represent these entities explicitly and comprehensively in the FMA in order to describe boundary and adjacency relationships of material physical anatomical entities and spaces. [43]

note(immaterial entity)[*Immaterial entities* are divided into two subgroups:

1. *boundaries* and *sites*, which bound, or are demarcated in relation, to *material entities*, and which can thus change location, shape and size as their material hosts move or change shape or size (for example: your nasal passage; the hold of a ship; the boundary of Wales (which moves with the rotation of the Earth) [38, 7, 10]);
2. *spatial regions*, which exist independently of *material entities*, and which thus do not change.]

note(continuant part of)[Immaterial entities /\*under 1. \*/are in some cases **continuant parts** of their material hosts. Thus the hold of a ship, for example, is a part of the ship; it may itself have parts, which may have names (used for example by ship stow planners, customs inspectors, and the like). Immaterial entities under both 1. and 2. can be of zero, one, two or three dimensions.

A site, e.g. the hull of a ship, as it moves through space, will occupy successively different spatial regions – Sites are in this respect, too, analogous to material entities. One site may move through another site, for instance the interior of a railway carriage through the Mont Blanc tunnel. Spatial regions never move through each other, because spatial regions never move. (More precisely: they are, by definition, at rest relative to the pertinent frame of reference.)

We define:

a(immaterial entity)[Definition: *a* is an *immaterial entity* = Def. *a* is an *independent continuant* that has no *material entities* as **parts**. [028-001]]

### Continuant fiat boundary

a(continuant fiat boundary)[Definition: *b* is a *continuant fiat boundary =* Def. *b* is an *immaterial entity* that is of zero, one or two dimensions and does not include a *spatial region* as **part**. [029-001]]

a(continuant fiat boundary)[ Axiom: Every *continuant fiat boundary* is **located at** some *spatial region* at every time at which it exists] (but not necessarily at the same spatial region from one time to the next) [XXX-001].

Intuitively, note(continuant fiat boundary)[a *continuant fiat boundary* is a boundary of some material entity (for example: the plane separating the Northern and Southern hemispheres; the North Pole), or it is a boundary of some immaterial entity (for example of some portion of airspace).

Three basic kinds of *continuant fiat boundary* can be distinguished (together with various combination kinds [29]):

* *continuant fiat boundaries* which delineate fiat parts within the interiors of material entities – for example the fiat boundary between the northern and southern hemispheres of the Earth; the North Pole; the fiat boundary which separates Utah from Colorado
* *continuant fiat boundaries* which delineate holes or cavities, for example fiat boundaries of the type referred to by the FMA as ‘plane of anatomical orifice’.
* combination *continuant fiat boundaries* suchas the border of Israel, which contains both rectilinear fiat boundaries along the border with Egypt and fiat boundaries tracking physical discontinuities on the Mediterranean side and along the borders with Syria and Jordan.

Note that boundaries are dependent entities, but they are not dependent in either of the senses of **s-** and **g-dependence** identified in BFO 2.0.]

#### Zero-dimensional continuant fiat boundary

a(zero-dimensional continuant fiat boundary)[Elucidation: A *zero-dimensional continuant fiat boundary* is a fiat point whose location is defined in relation to some *material entity*. [031-001]]

as(zero-dimensional continuant fiat boundary)[Examples: the geographic North Pole\; the quadripoint where the boundaries of Colorado, Utah, New Mexico, and Arizona meet\; the point of origin of some spatial coordinate system.]

#### One-dimensional continuant fiat boundary

a(one-dimensional continuant fiat boundary)[Elucidation: A *one-dimensional continuant fiat boundary* is a continuous fiat line whose location is defined in relation to some *material entity*. [032-001]]

as(one-dimensional continuant fiat boundary)[Examples: The Equator\, all geopolitical boundaries\, all lines of latitude and longitude\, the median sulcus of your tongue\, the line separating the outer surface of the mucosa of the lower lip from the outer surface of the skin of the chin. ]

To say that a one-dimensional continuant fiat boundary is *continuous* is to assert that it includes no gaps (thus it is a single straight or curved line).

#### Two-dimensional continuant fiat boundary

a(two-dimensional continuant fiat boundary)[Elucidation: a *two-dimensional continuant fiat boundary* (surface) is a self-connected fiat surface whose location is defined in relation to some *material entity*. [033-001]]

‘Self-connected’ is to be understood in the usual topological sense: thus an entity *b* is self-connected if and only if: given any two points in *b*, a continuous line can be traced in *b* which connects these points.

From this it follows that a two-dimensional continuant fiat boundary (surface) may have holes, as for example in the case of the surface of one side of a compact disk.

### Site

a(site)[Elucidation: *b* is a *site* means: *b* is a three-dimensional *immaterial entity* that is (partially or wholly) bounded by a *material entity* or it is a three-dimensional immaterial part thereof. [034-002]

Axiom: For every time *t* at which it exists, every *site* **occupies\_spatial\_region** some *three-dimensional spatial region* **at** *t*. [153-002]]

as(site)[Examples: a hole in the interior of a portion of cheese\, a rabbit hole\, the interior of your bedroom\, the Grand Canyon\, the Piazza San Marco\, an air traffic control region defined in the airspace above an airport\, the interior of a kangaroo pouch\, your left nostril (a fiat part – the opening – of your left nasal cavity) \, the lumen of your gut\, the hold of a ship\, the cockpit of an aircraft\, the interior of the trunk of your car\, the interior of your refrigerator\, the interior of your office\, [Manhattan Canyon](http://www.flickr.com/photos/tonyshi/4385628183/)). ]

Each immaterial entity coincides at any given time with some spatial region, but, as in the case of material entities, which spatial region this is may vary with time. As the ship moves through space, so its hold moves also. As you pinch and unpinch your nose, so your nasal passages shrink and expand.

The above elucidations of *site* and of the different kinds of *continuant fiat boundary* will be supplemented in a future version of BFO with definitions of *dimension* and **boundary dependence**.

Note: *Sites* may be bounded by various combinations of boundaries of different sorts [9]. Thus the Mont Blanc Tunnel is bounded by different sorts of fiat surfaces, including the plane rectilinear surfaces at either end.

Many of the terms used to refer to sites are ambiguous in that they are also used to refer to corresponding material entities. To say that ‘detergent is pumped into the tanksite’ is to assert that the detergent is pumped into the cavity which forms the interior of the tankmaterial\_entity (rather than into, say, the portion of metal which bounds this cavity). To say that ‘Mary lives in Salzburgsite’ is to assert not that Mary lives in a certain material collection of buildings, ashphalt, rocks, trees, and so forth, but rather that she lives in the spatial niche [7] bounded by this material collection.

A volume of class A controlled airspace associated with any given airport is a *site*, by our definition, since it is a three-dimensional continuant part of the *site* formed by the sum of this region with the portion of the class E region that is bounded by the surface of the Earth (see Figure 4).



Figure 4: [Airspace classes](http://ontology.buffalo.edu/smith/varia/controlledairspace/glos_aclass.jpg)

Cavities within what OGMS calls the ‘[extended organism](http://www.berkeleybop.org/obo/OGMS:0000087)’ are sites. Such sites are, following the FMA, parts of the organism only if they are part of its anatomical *Bauplan* [43, 44]*.* A cavity formed by a swallowed drug-capsule that is half-filled with powder is for this reason not a part of the organism. The cavity formed by the interior of the capsule that is not filled with powder is for the same reason not a part of the organism. These sites are however parts of the OGMS:*extended organism*.



5

### Spatial region

We recommend that users of BFOregionterms specify the coordinate frame in terms of which their spatial and temporal data are represented. When dealing with spatial regions on the surface of the Earth, for example, this will be the coordinate frame of latitude and longitude, potentially supplemented by the dimension of altitude. Lines of latitude and longitude are *two-dimensional* *continuant fiat boundaries* which move as the planet rotates and moves in its orbi around the sun; however, they are by definition at rest relative to the coordinate frame which they determine.

Given the terminology of spatial frames, we can elucidate ‘SpaceR’ as in BFO 1.1, as the maximal **instance** of the universal *spatial region*, relative to some frame R, as follows:

a(spatial region)[Elucidation: A *spatial region* is a *continuant entity* that is a **continuant\_part\_of** SpaceR as defined relative to some frame R. [035-001]]

‘Maximal’, in the above, means that any instance entity including spaceR as proper part is not a spatial region. SpaceR is, in common parlance, the whole of space (as defined in reference to some frame R). The term ‘SpaceR’ is the name of a certain particular. Similarly, TimeR (as defined in reference to some frame R) and Spacetime (which is independent of reference frame) are maximal instances of *temporal* and *spatiotemporal region*, respectively.

a(spatial region)[Axiom: All **continuant parts** of *spatial regions* are *spatial regions*. [036-001]]

Material entities have qualities of shape and size because they are located at *spatial regions* which instantiate corresponding shape and size universals.

Axiom: axiom(material entity)[Every *material entity* is located at some three-dimensional spatial region at every time at which it exists] [XXX-001]

*Object boundaries* and *sites* are distinguished from the spatial regions which they occupy at any given time as follows:

(1) *Object boundaries* and *sites* move when their material host moves, and they change shape or size when their material host changes shape or size.

(2) *Spatial regions* are, by definition, at rest relative to the pertinent coordinate frame.

#### Zero-dimensional spatial region

a(zero-dimensional spatial region)[Elucidation: A *zero-dimensional spatial region* is a point in SpaceR. [037-001]]

#### One-dimensional spatial region

a(one-dimensional spatial region)[Elucidation: A *one-dimensional spatial region* is a line or aggregate of lines stretching from one point in SpaceR to another. [038-001]]

a(one-dimensional spatial region)[Examples: an edge of a cube-shaped portion of SpaceR.]

A line is a connected one-dimensional spatial region.

#### Two-dimensional spatial region

a(two-dimensional spatial region)[Elucidation: A *two-dimensional spatial region* is a spatial region that is of two dimensions. [039-001]]

as(two-dimensional spatial region)[Examples: the surface of a sphere-shaped part of SpaceR\, an infinitely thin plane in SpaceR. ]

A surface is a connected one-dimensional spatial region.

#### Three-dimensional spatial region (a spatial volume)

a(three-dimensional spatial region)[Elucidation: A *three-dimensional spatial region* is a spatial region that is of three dimensions. [040-001]]

as(three-dimensional spatial region)[Examples: A cube-shaped region of SpaceR\, a sphere-shaped region of SpaceR.

]

### Location

#### The occupies\_spatial\_region relation

at(occupies\_spatial\_region)[Elucidation: b**occupies\_spatial\_region**r**at**tmeans that *r* is a spatial region in which independent continuant *b* is exactly located [041-002]]

a(occupies\_spatial\_region)[Domain: independent continuant]

a(occupies\_spatial\_region)[Range: spatial region]

**Occupies\_spatial\_region** is a primitive relation between an *independent continuant*, a spatial region which it occupies, and a time. This is a relation of exact location; the size, shape, orientation and location of *b* fit exactly to the size, shape and location of *r.* Thus for example if there are cavities in the interior of *b* then there are corresponding holes in the interior of *r.*

Clearly, normal usage will involve not the assertions of exact location captured by ‘**occupies\_spatial\_region**’, but rather more liberal statements for example: John is in London, Mary is in her hotel room, Carlo is in his mother’s womb, which are formulated using the **located\_in** relation as defined below.

a(occupies\_spatial\_region)[Axiom: every region *r* **occupies\_spatial\_region** *r* at all times. [042-002]]

a(occupies\_spatial\_region)[Axiom: if *b* **occupies\_spatial\_region** *r* **at** *t* & *b′* **continuant\_part\_of** *b* **at** *t*, then there is some *r′* which is **continuant\_part\_of** *r* **at** *t* such that *b′* **occupies\_spatial\_region** *r′* **at** *t*. [043-001]]

#### The located\_in relation

The **located\_in** relation links independent continuants which are not spatial regions..

at(located\_in)[Definition: b**located\_in** c **at**t = Def. b and c are independent continuants, and the region **at** which b is **located at** t is a (proper or improper) **continuant\_part\_of** the region **at** which c is **located at** t. [045-001] ]

a(located\_in)[Domain: independent continuant]

a(located\_in)[Range: independent continuant]

as(located\_in)[Examples: your arm **located\_in** your body\; this stem cell **located\_in** this portion of bone marrow\; this portion of cocaine **located\_in** this portion of blood\; Mary **located\_in** Salzburg\; the Empire State Building **located\_in** New York. ]

at(located\_in)[Theorem: **Located\_in** is transitive. [046-002] /\*

That is to say:

If *b* **located\_in** *c* **at** t and *c* **located\_in** *d* **at** t, then *b* **located\_in** *d* ***at*** *t* \*/]

as(independent continuant)[Axiom: For any *independent continuant* *b* and any *t* there is some *spatial region r* such that *b* is **located\_in** *r***at** *t.* [134-001]

Axiom: For any *independent continuant* *b* and any *t*, if *b* is **located\_in** *r***at** *t* then there is some region *r′* that is **continuant\_part\_of** *r* and such that *b* **occupies\_spatial\_region** *r′* **at** *t.* [135-001]]

For all independent continuants *a* and *b*, parthood implies location:

at(continuant\_part\_of)[Axiom: if *b* **continuant\_part\_of** *c* **at** *t* and *b* is an independent continuant, then *b* is **located\_in** *c* **at** *t.* [047-002] ]

Note that the converse of this axiom does not hold: independent continuants are located in sites, as Mary, today, is **located\_in** Salzburg, yet Mary is not a part of Salzburg.

Sites and boundaries may stand in the **located\_in** relation also in their own right, as for example when we say that 5th Avenue is **located in** New York, or that a portion of the Franco-German boundary is **located in** the Rhein valley.

#### Problem cases for the located\_in relation

As pointed out in [52] there are problem cases for the **located\_in** relation. Consider, for example an insect located near the stem of a wine glass. Is the insect then **located\_in** the wine glass? Are crumbs placed in the hole of a donut to be counted as **located\_in** the donut? Users of **located\_in** should use an intuitive test in resolving such questions by ascertaining whether, where *b* is not in the interior of *c* but is rather in some hole or cavity attached to *c*’s outer boundary, the hole in question is one which is fillable in the sense defined by Casati and Varzi [52]. The cup-shaped hole in the wine glass is fillable in this sense; not however the concave spaces around the stem.

#### Chaining rules

a(located\_in)[Axiom: for all independent continuants *b*, *c*, and *d*,and all times *t*: if *b* **continuant\_part\_of** *c* **at** *t* & *c* **located\_in** *d* **at** *t*, then *b* **located\_in** *d* **at** *t*. [048-002]]

a(located\_in)[Axiom: for all independent continuants *b*, *c*, and *d*,and all times *t*: if *b* **located\_in** *c* **at** *t* & *c* **continuant\_part\_of** *d* **at** *t*, then *b* **located\_in** *d* **at** *t*. [049-001]]

## Specifically dependent continuant

a(specifically dependent continuant)[Definition: *b* is a *specifically dependent continuant* =Def. *b* is a *continuant* & there is some *independent continuant* *c* which is not a *spatial region* and which is such that *b* **s-depends\_on** *c* **at** every time*t* during the course of *b*’s existence. [050-003]

a(specifically dependent continuant)[Definition: *b* is a *relational specifically dependent continuant* =Def. *b* is a *specifically dependent continuant* and there are *n* >1independent continuants *c*1, … *cn* which

1. are not spatial regions
2. are such that for all *i*, *j,* where1 ≤ *i < j* ≤ *n*, *ci* and*cj*share no common parts **at** every time during the course of *b*’s existence,
3. are such that for each *i,* where1 ≤ *i* ≤ *n*, *b* **s-depends\_on** *ci* **at** every time *t* during the course of *b*’s existence [131-004].]

as(specifically dependent continuant)[Examples: of *one-sidedly* *specifically dependent continuants*: the mass of this tomato\, the pink color of a medium rare piece of grilled filet mignon at its center\, the smell of this portion of mozzarella\, the disposition of this fish to decay\, the role of being a doctor\, the shape of this hole the function of this heart: to pump blood\.]

as(specifically dependent continuant)[Examples: of *relational specifically dependent continuants* (multiple bearers): John’s love for Mary, the ownership relation between John and this statue, the relation of authority between John and his subordinate.]

John’s ownership of his statue is an instance of an ownership relation, a relational specifically dependent continuant that starts to exist at a certain time and ceases to exist at some later time, for example because the statue is destroyed.

Intuitively **s-dependence** holds only where the **s-dependent** entity or entities have no material parts. The accused in a court of law has an **s-dependent** *role*, but he himself is a human being, and thus not an **s-dependent** entity.

at(s-depends on)[Axiom: If *b* is**s-depends\_on** something at some time, then *b* is not a *material entity.* [052-001]]

### The inheres\_in and bearer\_of relations

at(inheres\_in)[Definition: *b* **inheres\_in** *c* **at** *t* =Def. *b* is a *dependent continuant* & *c* is an *independent continuant* that is not a *spatial region* & *b* **s-depends\_on** *c* **at** *t*. [051-002]]

a(inheres\_in)[Domain: *specifically dependent continuant*]

a(inheres\_in)[Range: *independent continuant* that is not a *spatial region*]

note(inheres\_in)[**Inherence** is a subrelation of **s-depends\_on** which holds between a *dependent continuant* and an *independent continuant* that is not a *spatial region*. Since s-dependent continuants cannot migrate from one independent continuant bearer to another, it follows that if *b* **s-depends\_on** independent continuant*c* at some time, then *b* **s-depends\_on** *c* at all times at which *a* exists. Inherence is in this sense redundantly time-indexed.

For example, consider the particular instance of openness inhering in my mouth **at** t as I prepare to take a bite out of a donut. This is followed by a closedness **at** t +1 when I bite the donut and start chewing. This openness instance is then shortlived, and to say that it**s-depends\_on** my mouth at all times at which it exists, means: at all times during this short life. Every time you make a fist, you make a new (instance of the universal) fist.(Every time your hand has the fist-shaped quality, there is created a new, short-lived instance of the universal fist-shaped quality.)]

at(bearer\_of)[Definition: *b* **bearer\_of** *c* **at** *t =*Def. *c* **s-depends\_on** *b* **at** *t* & *b* is an *independent continuant* that is not a *spatial region.* [053-005]]

a(bearer\_of)[Domain: *independent continuant* that is not a *spatial region*]

a(bearer\_of)[Range: *specifically dependent continuant* or *occurrent*]

**Bearer\_of** in contrast to inherence, is not redundantly time-indexed, since if *b* is a bearer of some *c* only at some time during which *b* exists, but *c* cannot similarly inhere in *b* only at some times during which *c* exists.

### No s-dependence of higher order

BFO does not recognize universals of higher order (for example, the universal *universal*). Thus all universals are instantiated by instance entities, which are not universals.

Similarly, BFO does not recognize **s-dependence** of higher order. Thus there are no **s-dependence** structures of this sort:

*a*

*b*

*c*

Figure 6: Higher-order dependence

If *b* is dependent on *c* and *c* is dependent on *d* then it must be that there obtains some structure as in Figure 7:

*b*

*c*

*d*

*b*

*c*

*d*

Figure 7: Examples of (left:) *Mutual dependence* and (right:) *transitive dependence*

In case of mutual dependence (Figure 7, left), *b* and *c* areboth (one-sidedly) dependent on *d* and (mutually) dependent on each other.

Cases like those on the left in Figure 7 may be called mutually s-dependent continuants:

as(specifically dependent continuant)[Examples of *mutually* *specifically dependent continuants*: the function of this key to open this lock and the mutually dependent disposition of this lock: to be opened by this key\; the mutual dependence of the role *predator* and the role *prey* as played by two organisms in a given interaction\; the mutual dependence of proton donors and acceptors in chemical reactions [79].

legally ]

In ruling out structures of the sort illustrated in Figure 6, BFO affirms that there are, for example, no qualities of roles and no roles of qualities. however, there are qualities – such as the quality of pressure and temperature of a body of gas in a certain container – which are both dependent on each other and on their common bearer (left side of Figure 7).

There are no dispositions of qualities and no functions of dispositions. And there are no higher order processes in which processes themselves would change. (See the section on Process Profiles below.) In all such cases, the recommendation on developers of BFO-conformant ontologies is to seek a relevant relatumin the underlying material bearer (the *thing* or *res*), called ‘material basis’ in what follows.Thus if a blood vessel has the quality of being constricted, then it is the blood vessel itself, and not the quality of constrictedness, that has the disposition: to block the flow of blood.

In a sense, therefore, qualities of qualities are qualities of the underlying bearer. The shape of the redness on John’s arm, for example, is not a quality of the redness, it is, like the redness itself, a quality of a certain (fiat) portion of the surface of the arm.

The above can be summarized as follows:

a(s-depends on)[Axiom: If *b* **s-depends\_on** *c* **at***t* & *c***s-depends\_on** *d* **at***t* then *b* **s-depends\_on** *d* **at***t*. [054-002] ]

Mutual dependence and transitive chains such as are illustrated in Figure 7 always bottom out in some independent continuant that is not a spatial region.

a(s-depends-on)[THEOREM: If *b* **s-depends\_on** something **at** *t*, then there is some *c*, which is an independent continuant and not a spatial region, such that *b* **s-depends\_on** *c* **at** *t.* [136-001]]

Note that this theorem applies both to s-dependent continuants and to occurrents. Every occurrent that is not a temporal or spatiotemporal region is **s-dependent** on some independent continuant that is not a spatial region]. (The theorem does not apply to sites and continuant fiat boundaries, but something similar will be seen to hold when the relation of **boundary\_depends\_on** is introduced in a future version of BFO.)

### Quality

BFO 2.0 distinguishes two major families of *s-dependent continuants*, namely *qualities* and *realizable dependent continuants.* (Again, no claims are made as to the exhaustiveness of this classification.) Solubility, in order to be realized or manifested, requires a dissolving process which has some solid piece of, for example, salt or sugar as participant. Their crystalline quality, in contrast, does not stand in need of any realization process of this sort.

a(quality)[Elucidation: a *quality* is a *specifically dependent continuant* that, in contrast to roles and dispositions, does not require any further process in order to be realized. [055-001]]

a(quality)[Examples: the color of a tomato\, the ambient temperature of this portion of air\, the length of the circumference of your waist, the shape of your nose, the shape of your nostril\, the mass of this piece of gold. ]

Note that in the above list of examples we encounter a further type of dependence, turning on the fact that, for example, the color of a tomato depends in some sense on processes involving photons. This type of dependence is not dealt with in this specification, but it will be treated in a future version of BFO.

*Quality* is a rigid universal:

a(quality)[Axiom: If an *entity* is a *quality* at any time that it exists, then it is a *quality* at every time that it exists. [105-001] ]

at(quality\_of)[Definition: *b* **quality\_of** *c* **at** *t =* Def. *b* is a *quality* & *c* is an *independent continuant* that is not a *spatial region* & *b* **s-depends\_on** *c* **at** *t*. [056-002]

Domain: *quality*

Range: *independent continuant* that is not a *spatial region*]

Sites have qualities of size and shape. But spatial regions, like regions in general, do not have qualities (they are not the sorts of things which can be bearers of s-dependent continuants, just as they are not the sorts of things that can be participants in processes – in the strict BFO sense of ‘s-dependence’ and ‘participant’). Rather, spatial regions instantiate corresponding universals. Thus a spherical spatial region of diameter 3 meters instantiates the universal *3-meter-diamter spherical spatial region*.

#### Relational quality

There are relational qualities, which have a plurality of *independent continuants* as their bearers [6].

a(relational quality)[Definition: *b* is a *relational quality =* Def. for some *independent continuants* *c*, *d* and for some time *t*: *b* **quality\_of** *c* **at** *t* & *b* **quality\_of** *d* **at** *t*. [057-001]]

a(relational quality)[Examples: a marriage bond, an instance of love, an obligation between one person and another. ]

These are relational specifically dependent continuants as described above.

Examples of relational *processes* such as kissing or hitting are discussed below.

Relational qualities, like qualities in general, are entities in their own right; relational processes such as kissing or hitting are also entities in their own right; they are, in the jargon, *extra ingredients of being*. This means that they have counterparts both on the level of instances and on the level of universals. Relations such as **instance\_of** or **part\_of**, in contrast, for which it does not make sense to speak of instances, are not entities in their own right. If Mary is a *human being*thenthere is similarly no extra entity – for example, no instance of the relation of instantiation – that is needed to make this true.

Internal relations such as comparatives (*larger-than*, *heavier-than …*) are also not entities in their own right. If John is taller than Mary, then this is accounted for exclusively in terms of John’s and Mary’s respective height qualities, and in terms of the fact (not an extra entity in the BFO sense) that each of these heights instantiates a certain determinate height universal and that the totality of such universals form a certain linear order.

### Realizable entity

a(realizable entity)[Elucidation: To say that *b* is a *realizable entity* is to say that *b* is a *specifically dependent continuant* that inheres in some *independent continuant* which is not a *spatial region* and is of a type instances of which are **realized** in *processes* of a correlated type. [058-002]

]a(realizable entity)[Examples: the role of being a doctor\, the function of your reproductive organs\, the disposition of your blood to coagulate\, the disposition of this piece of metal to conduct electricity.]

Here examples of correlated process types are, respectively: diagnosing, inseminating, formation of a clot, transmission of an electric current, demarcating a fiat, geopolitical border.

#### Relation of realization

at(realizes)[Elucidation: to say that *b* realizes *c* ***at*** *t*  is to assert that

there is some *material entity d*

& *b* is a *process* which **has participant** *d* **at** t

& *c* is a *disposition* or *role* of which *d* is **bearer\_of** **at** *t*

& the type instantiated by *b* is correlated with the type instantiated by *c*. [059-003]

Domain: process

Range: realizable entity]

a(realized-in)[Theorem: if a realizable entity *b* is realized in a process *p*, then *p* stands in the **has\_participant** relation to the bearer of *b*. [106-002] ]

a(realizable entity)[Axiom: All *realizable dependent continuants* have *independent continuants* that are not *spatial regions* as their bearers. [060-002] ]

There are mutually *realizable dependent continuants* in the sense defined above (e.g. the mutually dependent husband and wife roles, as described in [28, 79]).

### Role (externally-grounded realizable entity)

a(role)[Elucidation: *b* is a *role* means:

*b* is a *realizable entity*

& *b* exists because there is some single bearer *c* that is in some special physical, social, or institutional set of circumstances in which this bearer does not have to be

& *b* is not such that, if it ceases to exist, then the physical make-up of the bearer *c* is thereby changed. [061-001]]

as(role)[Examples: the priest role, \, the student role, \, the role of subject in a clinical trial, \, the role of a stone in marking a property boundary, \, the role of a boundary to demarcate two neighboring administrative territories\, the role of a building in serving as a military target.]

‘Role’ is another name for what we might call an extrinsic or externally-grounded realizable entity. An entity has a certain role not because of the way it itself is, but because of something that happens or obtains externally, for example a student is enrolled in an institution of learning, a patient is enrolled in a clinical trial.

Note that the elucidation above incorporates a hypothesis to the effect that there are no *relational roles*. In other words, each role is the role of exactly one bearer.

#### Optionality of roles

Because a role is not a consequence of the in-built physical make-up of its bearer, roles are *optional* in the sense that the bearer of a role can lose this role without being thereby physically changed. Roles characteristically involve some form of social ascription or imputation.

Some qualities and dispositions are non-optional in the sense that, if they cease to exist, then their bearer ceases to exist. (Consider for example the quality *mass.*) Such cases imply a new form of dependent that will be dealt with in a future version of BFO.

#### Having a role vs. playing a role

An entity is sometimes said to play a role, as when a passenger on a commercial airline plays the role of pilot in an emergency, or when a pyramidal neuron plays the role occupied by a damaged stellar neuron in the brain; but then neither the person nor the pyramidal neuron have those roles. BFO 2.0 only specifies the **has\_role** relation.

### Disposition (internally-grounded realizable entity)

a(disposition)[Elucidation: *b* is a disposition means:

*b* is a *realizable entity*   
& *b*’s bearer is some *material entity*   
& *b* is such that if it ceases to exist, then its bearer is physically changed,   
& *b*’s realization occurs when and because this bearer is in some special physical circumstances,   
& this realization occurs in virtue of the bearer’s physical make-up. [062-002]]

as(disposition)[Examples: an atom of element X has the disposition to decay to an atom of element\, the cell wall is disposed to filter chemicals in endocitosis and exocitosis\, certain people have a predisposition to colon cancer\, children are innately disposed to categorize objects in certain ways.]

There are no relational dispositions. Thus each disposition is the disposition of exactly one bearer. (Note, however, that we might affirm of patient John that he has the disposition we call *liver cirrhosis*; John is then the bearer of the disposition in one sense; but his liver is the bearer in another sense – as discussed in the OGMS ontology [27].

Unlike roles, dispositions are not optional. It is because an entity is a certain way that it has a certain disposition, and if its physical makeup is changed then it may lose that disposition. A disposition can for this reason also be referred to as an *internally-grounded realizable entity*. That is, it is a realizable entity that is a reflection of the (in-built or acquired) physical make-up of the *material entity* in which it **inheres**.

a(disposition)[Axiom: If *b* is a realizable entity then for all *t* **at** which b **exists**, *b* **s-depends\_on** some material entity **at** *t*. [063-002]]

note(disposition)[Dispositions exist along a strength continuum. Weaker forms of disposition are realized in only a smaller, stronger forms in a larger number of triggering cases [89, 92].

Each disposition type is associated with one or more characteristic *realization* process types – types which are instantiated by those processes in which the respective disposition instance is realized. Dispositions may also be associated with characteristic *trigger* process types – instantiated by processes (for example, for the disposition we call ‘fragility’, the process of being dropped on a hard surface) which give rise to the processes in which they are realized. The term ‘causality’ is often applied to refer to such trigger-and-realization process pairs. BFO does not yet incorporate a theory of causality, though it is presumed that any such theory will take such process pairs – alongside our treatment of types of causal unity in section 3.5.1 above – as its starting point.]

### Function

a(function)[Elucidation: A *function* is a disposition that exists in virtue of the bearer’s physical make-up and this physical make-up is something the bearer possesses because it came into being, either through evolution (in the case of natural biological entities) or through intentional design (in the case of artifacts), in order to realize processes of a certain sort. [064-001]]

as(function)[Examples: the function of amylase in saliva to break down starch into sugar\, the function of a hammer to drive in nails\, the function of a heart pacemaker to regulate the beating of a heart through electricity.]

Functions are realized in processes which can be referred to colloquially as functionings. Each function has a bearer with a specific type of physical make-up. This is something which, in the biological case, is of a type which has naturally evolved to carry this function (as in a hypothalamus secreting hormones). In the artifact case, it is something which is of a type which is the result of design (as in an Erlenmeyer flask designed to hold liquid) or also has been deliberately selected for as in the case of penicillin. The cavity (site) in the interior of the flask does not have a function in its own right, but only by inheritance from its material host.

It is not accidental or arbitrary that a given eye has the function to see or that a given screwdriver has been designed and constructed with the function of fastening screws. Rather, these functions are integral to these *entities* in virtue of the fact that the latter have evolved, or been designed and constructed, to have a corresponding physical make-up. Thus the heart’s function is to pump blood, and not merely to produce thumping sounds. The latter are by-products of the heart’s proper functioning. The screwdriver’s function is in addition bound together with the function of the screw: the two are mutually dependent on each other – a case of mutual generic dependence (see below), since the screwdriver function can be realized with the aid of many different screws, and the screw’s function with the aid of many different screwdrivers.

Like dispositions of other sorts, a function is an internally-grounded realizable entity: it is such that, if it ceases to exist, then its bearer is physically changed. In some cases an entity may preserve its function even while it is physically changed in ways which make it unable to function. If a lung or attic fan is non-functioning this is an indication that the physical make-up of these things has changed – in the case of the lung perhaps because of a cancerous lesion; in the case of the attic fan because of a missing screw. But these entities then still *have their functions*; it is simply that they are unable to exercise these functions until the physical defect is rectified, for example through clinical intervention or mechanical repair. The entities would *lose* their function only if they were changed drastically, which means: beyond repair.

Note(function)[In [26], we distinguished two varieties of function, artifactual and biological. These are not asserted subtypes of BFO:*function* however, since the same function – for example: to pump, to transport – can exist both in artifacts and in biological entities. The asserted subtypes of *function* that would be needed in order to yield a separate monohierarchy are not artifactual function, biological function, etc.; rather they are: transporting function, pumping function, etc.]

#### Defined relations

at(role\_of)[Definition: *a* **role\_of** *b* **at***t* =Def. *a* is a role and *c* **inheres\_in** *b* **at** *t.* [065-001]]

at(disposition\_of)[Definition: *c* **disposition\_of** *b* **at** *t* =Def. *c* is a disposition and *c* **inheres\_in** *b* **at** *t.* [066-001] ]

at(function\_of)[Definition: *c* **function\_of** *b* **at** *t* =Def. *c* is a function and *c* **inheres\_in** *b* **at** *t.* [067-001] ]

a(has\_role)[Definition: *c* **has\_role** *b* **at** *t* =Def. *b* **role\_of** *c* **at** *t.* [068-001] ]

at(has\_disposition)[Definition: *c* **has\_disposition** *b* **at** *t* =Def. *b* **disposition\_of** *c* **at** *t.* [069-001] ]

at(has\_function)[Definition: *c* **has\_function** *b* **at** *t* =Def. *b* **function\_of** *c* **at** *t.* [070-001] ]

### Material basis

Dispositions (and thus also functions) are introduced into BFO in order to provide a means for referring to what we can think of as the potentials or powers of things in the world without the need to quantify over putative ‘possible worlds’ or ‘possible objects’. Whenever a disposition exists, then it is a disposition of some material bearer. Dispositions exist in every case because there is some corresponding portion of reality – some part of this material bearer – that is non-dispositional in nature, which we call the material basis of the disposition. The relevant relation can be elucidated as follows:

at(has\_material\_basis)[Elucidation: *b* **has\_material\_basis** *c* **at** *t* means:

*b* is a *disposition*

& *c* is a *material entity*

& there is some *d* **bearer\_of** *b* **at** *t*

& *c* **continuant\_part\_of** *d* **at** t

& *d* **has\_disposition** *b* **at** *t* because *c* **continuant\_part\_of** *d* **at** *t*. [071-002] ]

as(has\_material\_basis)[Examples: the material basis of John’s disposition to cough is the viral infection in John’s upper respiratory tract\; the material basis of the disposition to wear unevenly of John’s tires is the worn suspension of his car. ]

In some cases the material basis is associated with a certain quality. Thus if a portion of glass is transparent, then the material basis of this transparency is the portion of glass itself. But more can be said, namely that the transparency obtains because the molecules in this portion of glass *are currently* organized in a certain way, thus the aggregate of molecules has a quality: lattice structure.

The material basis of the transparency of this glass is the molecules arranged in a certain lattice structure. The material basis of the color of this ball is molecules in the first few molecular layers of the outside of the ball arranged in a certain (light-reflecting) way.

## Generically dependent continuant

at(g-depends on)[Elucidation: *b* **g-depends on** *c* **at** *t*1 means: *b* exists **at** *t*1 and *c* exists **at** *t*1

& for some type *B* it holds that

(*c* **instantiates** *B***at** *t*1)

& necessarily, for all *t* (if *b* exists **at *t*** then some **instance\_of** *B* exists **at** *t*)

& not (*b* **s-depends\_on** *c* **at** *t*1). [072-002]]

a(g-depends on)[Domain: *generically dependent continuant*]

a(g-depends on)[Range: *independent continuant*]

a(g-depends on)[Axiom: if *b* **g-depends\_on** *c* at some time *t*, then *b* **g-depends**\_**on** something at all times at which *b* exists. [073-001] ]

a(generically dependent continuant)[Definition: *b i*s a *generically dependent continuant* = Def. *b* is a *continuant* that **g-depends\_on** one or more other *entities*. [074-001] ]

As we saw, BFO’s *specifically dependent continuants* are subject to the axiom of non-migration – they cannot migrate from one bearer to another. *Generically dependent continuants*, in contrast, can in a sense migrate, for example through the process of exact copying which allows the very same information artifact to be saved to multiple storage devices.

We can think of *generically dependent continuants*, intuitively, as complex continuant patterns (complex qualities) of the sort created by authors or designers, or (in the case of DNA sequences) through the processes of evolution. Further examples of *generically dependent continuants* include: the chessboard pattern, the Coca Cola logo, the pattern of a traffic sign. Each such pattern exists only if it is **concretized** in some counterpart *specifically dependent continuant* – the pattern of black and white squares on this wooden chessboard here; the pattern of red and white swirls on the label of this Coca Cola bottle; the pattern of paint on this traffic signboard.

Such patterns can be highly complex. A certain pattern (of letters of the alphabet and associated punctuation and spacing) which is a work of literature is concretized in the patterns of ink marks in this and that particular *copy* of the work. When you create a novel then in addition to creating an **s-dependent** pattern of inkmarks on your manuscript, you create also a particular instance of the *generically dependent continuant* type *novel*. When you print further copies in book form, then you create multiple particular instances of the *independent continuant* type *book.*

### Relation of concretization

a(concretizes)[Elucidation: *b* **concretizes** *c* **at** *t* means*:*

*b* is a specifically dependent continuant

& *c* is a generically dependent continuant

& for some independent continuant that is not a spatial region *d*,

*b* **s-depends\_on** *d* **at** *t*

& *c* **g-depends** on *d* **at** *t*

& if *c* migrates from bearer *d* to another bearer *e* than a copy of *b* will be created in *e*. [075-002]

Domain: specifically dependent continuant

Range: generically dependent continuant]

example(generically dependent continuant)[The entries in your database are patterns instantiated as *quality* instances in your hard drive. The database itself is an aggregate of such patterns. When you create the database you create a particular instance of the *generically dependent continuant* type *database*. Each entry in the database is an instance of the *generically dependent continuant* type [IAO: *information content entity*](http://purl.obolibrary.org/obo/IAO_0000030).]

Databases, pdf files, novels, proper names, serial numbers, and other information artifacts are analogous to other created artifacts such as paintings or sculptures. They differ from the latter, however, in that, once they have been created, they can exist in many copies. These many copies exist because of a templating process. Because such a templating process exists, we have examples of the sorts of patterns that are *generically dependent* continuants.

*Generically dependent continuants* can be **concretized** in multiple ways; example(concretizes)[you may concretize a poem as a pattern of traces on an audio tape\. You may concretize a piece of software by installing it in your computer\. You may concretize a recipe that you find in a cookbook by turning it into a plan which exists as a *realizable dependent continuant* in your head.]

a(concretizes)[Axiom: if *b* **g-depends** on *c* at some time *t*, then there is some *d*,such that *d* **concretiz**es *b* **at** t and *d* **s-depends\_on** *c* **at** *t.* [076-001]]

### Works of music and experimental protocols

In the case of a work of music such as Beethoven’s *9th Symphony*, there is a certain abstract pattern, a *generically dependent continuant*, which we shall call #9. #9 is an **instance** of the type *symphony*, which is itself a subtype of the type *musical work*. #9 is **concretized** in certain *specifically dependent continuant* patterns of ink marks that we find in printed copies of the *score*, or (for example) in certain *specifically dependent continuant* patterns of grooves in vinyl disks. The score is an **instance** of the *generically dependent continuant* type *plan specification*, specifying how to create a corresponding *musical performance*. This *plan specification* is **concretized** in distributed fashion in the form of a network of subplans distributed across the minds of the conductor and the members of the orchestra, together forming a plan to create a musical performance of #9. This complex *realizable dependent continuant* is then **realized** when conductor and orchestra work together to create a certain pattern of air vibrations conforming to the score and audible to an audience through certain associated patterns of excitations of their auditory nerves. One consequence of the above is that we cannot in fact listen to Beethoven’s 9th Symphony, but rather only to performances thereof.

Analogously, when a research team decides to perform an experiment following a published protocol, the protocol itself is a *generically dependent continuant* **instance** of the type *plan specification*. The leader of the research team concretizes this protocol in her mind to create that *specifically dependent realizable continuant* which is her plan for carrying out this experiment. At the same time she creates a series of sub-protocols, which are plan specifications for each of her various team members. Each of the latter is then concretized in the mind of the appropriate team member as a plan for carrying out corresponding subactivities within the experiment. The experiment itself is the total *realization* of these plans, having outputs such as publications, databases, and so forth, as described in the [Ontology for Biomedical Investigations](http://obi-ontology.org/page/Main_Page) (OBI).

## Occurrent

a(occurrent)[Elucidation: An *occurrent* is an entity that unfolds itself in time or it is the instantaneous boundary of such an entity (for example a beginning or an ending) or it is a temporal or spatiotemporal region which such an entity occupies. [077-002]]

note(process)[The realm of occurrents is less pervasively marked by the presence of natural units than is the case in the realm of independent continuants. Thus there is here, on the *occurrent* side, no counterpart of ‘object’ on the side of BFO:*continuant*. In BFO 1.0 ‘process’ served as such a counterpart. In BFO 2.0 ‘process’ is, rather, the occurrent counterpart of ‘material entity’. Those natural – as contrasted with engineered, which here means: deliberately executed – units which do exist in the realm of occurrents are typically either parasitic on the existence of natural units on the continuant side, or they are fiat in nature. Thus we can count *lives*; we can count football games; we can count chemical reactions performed in experiments or in chemical manufacturing. But we cannot count the processes taking place, for instance, in an episode of insect mating behavior, just as we cannot count the portions of water contained in a given ‘behavior’ is a mass noun

Even where natural units are identifiable, for example cycles in a cyclical process such as the beating of a heart or an organism’s sleep/wake cycle, the processes in question form a sequence with no discontinuities (temporal gaps) of the sort that we find for instance where billiard balls or zebrafish or planets are separated by clear spatial gaps. Lives of organisms are process units; but they too unfold in a continuous series from other, prior processes such as fertilization, and they unfold in turn in continuous series of post-life processes such as post-mortem decay. Clear examples of boundaries of processes are almost always of the fiat sort (midnight, a time of death as declared in an operating theater or on a death certificate, the initiation of a state of war)].

### Relation of temporal parthood

We introduced above the relation **occurrent\_part\_of**. We can now identify in its terms the sub-relation **temporal\_part\_of** which holds between two occurrents when the former is a phase or subprocess (a slice or segment) of the latter:

*timee*

**process *p****e*

**temporal**

**part of process *p*****

a(temporal\_part\_of)[Definition: *b* **temporal\_part\_of** *c* =Def.

*b* **occurrent\_part\_of** *c* &

& for some *temporal region t*, *b* occupies\_temporal\_region *t*

& for all *occurrents* *d*, *t*′ (if *d* **occupies\_temporal\_region** *t*′ & *t* **occurrent\_part\_of***t*

then (*d* **occurrent\_part\_of** *a* iff *d* **occurrent\_part\_of** *b*)). [078-003]]

Thus *b* is exactly the restriction of *c* to *t*. example(occurrent part of)[The process of a footballer’s heart beating once is an **occurrent part** but not a **temporal\_part** of a game of football.]

as(temporal\_part\_of)[Examples: your heart beating from 4pm to 5pm today is a **temporal part** of the *process* of your heart beating\; the 4th year of your life is a **temporal part** of your life\. The first quarter of a game of football is a **temporal part**ofthe whole game\. The process of your heart beating from 4pm to 5pm today is a **temporal part** of the entire process of your heart beating.\ The 4th year of your life is a **temporal part** of your life\, /\* as is\*/ the process boundary which separates the 3rd and 4th years of your life. ]

a(temporal\_part\_of)[Definition: *b* **proper\_temporal\_part\_of** *c* =Def. *b* **temporal\_part\_of** *c* & not (*b* = *c*). [116-001]]

a(temporal\_part\_of)[Theorem: If *b* **proper\_temporal\_part\_of** *c*, then there is some *d* which is a**proper\_temporal\_part\_of** *c*and which shares no parts with *b.* [117-002]]

This follows from the axiom of Weak Supplementation of Minimal Extensional mereology.

Temporal parts are often referred to as as ‘stages’ or ‘phases’ of an occurrent.

a(occurrent)[Axiom: *b* is an *occurrent* entity iff *b* is an entity that has **temporal parts**. [079-001]]

Since *temporal regions* are **temporal parts** (though not **temporal proper parts**) of themselves, this means, in particular, that *zero-dimensional temporal regions* (temporal instants) are also *occurrents*.

Subtypes of *occurrent* are:

process

complete process

history

sectional process

process profile

process boundary

temporal region

zero-dimensional temporal region

one-dimensional temporal region

spatiotemporal region

### Projection relations

a(projects\_onto)[Elucidation: To say that spatiotemporal region *s* **temporally\_projects\_onto** temporal region *t* is to say that *t* is the temporal extension of *s.* [080-004]]

a(projects\_onto)[Elucidation: To say that spatiotemporal region *s* **spatially\_projects\_onto** spatial region *r* **at** *t* is to say that *r* is the spatial extension of *s* **at** *t.* [081-003]

Axiom: The result of projection is unique in each case (relative to some frame).

Every spatiotemporal region projects onto some temporal region, and at every time instant within its extent onto some spatial region (all of this relative to some frame).

### The occupies relations, and occurs\_in relation

a(occupies\_spatiotemporal\_region)[Elucidation: p**occupies\_spatiotemporal\_region** s. This is a primitive relation between an *occurrent p* and the *spatiotemporal region* *s* which is its spatiotemporal extent. [082-003]

Domain: *occurrent*

Range: *spatiotemporal region*]

a(occupies\_temporal\_region)[Elucidation: p**occupies\_temporal\_region** t. This is a primitive relation between an *occurrent* *p* and the *temporal* *region t* upon which the *spatiotemporal region p* **occupies\_spatiotemporal\_region projects**. [132-001]

Domain: *occurrent*

Range: *temporal region*

Axiom: Every *temporal* *region* **occupies\_temporal\_region** itself. [137-001]

Axiom: For every occurrent *p* there is some unique *spatiotemporal region s* such that *p* occupies *s.* [XXX-001] ] ]

note(occupies\_spatiotemporal\_region)[The **occupies\_spatiotemporal\_region** and **occupies\_temporal\_region** relations are the counterpart, on the *occurrent* side, of the relation **occupies\_spatial\_region.**]

a(occurs\_in)[Definition: *b* **occurs\_in** *c* =def

*b* is a *process* and *c* is a *material entity* or *immaterial entity*

*&* there exists a spatiotemporal region *s* and *b* **occupies\_spatiotemporal\_region** *s*

& forall *t*, if *b* exists\_at *t* then *c* exists\_at *t*

& there exist *spatial regions r* and *r′* where

& *b* **spatially\_projects\_onto** *r* **at** *t*

& *c* **occupies\_spatial\_region** *r′* **at** *t*

& *r* is a **proper\_continuant\_part\_of** *r′* **at** *t* [XXX-001]]

## Processes and process boundaries

### Process

a(process)[Definition: *p* is a *process* = Def. *p* is an *occurrent* that has **temporal proper parts** and for some time *t*, *p* **s-depends\_on** some *material entity* **at** *t*. [083-003]]

as(process)[Examples: the life of an organism\, a process of sleeping\, a process of cell-division, \ a beating of the heart\, a process of meiosis\, the course of a disease\, the flight of a bird\, your process of aging. ]

Just as there are relational qualities, so also there are relational processes, which **s-depend\_on** multiple material entities as their relata.

Examples of relational processes: John seeing Mary [1, 4], a moving body’s crashing into a wall, a game of snooker, the videotaping of an explosion.

#### Complete and partial process

A complete (or ‘full’ or ‘plenary’) process is defined as follows (continuing our discussion of Zemach in section 2.12 above):

Definition: *complete process* =Def. a *process* that is identical with the sum of all *processes* occurring in a given *spatiotemporal region*.

When a process falls short of being complete we refer to it is a partial (or ‘sectional’ or ‘incomplete’) process. Examples of partial processes are the spinning of a spinning top and the simultaneous warming up of the spinning top during the period when it is being spinned.

#### History

Histories are one important subtype of complete process.

as(history)[Elucidation: A *history* is a *complete process* that is the sum of the totality of *processes* taking place in the *spatiotemporal region* **occupied** by a *material entity* or *site*. [138-001]]

The history of a *material entity* will include, on the above account, the movements of neutrinos within the interior of the entity as they pass through. In OGMS we define the *life* of an organism as the *history* of a material entity called the *extended organism*, which is the mereological sum of an organism and all material entities located within the organism, overlapping the organism, or occupying sites formed in part by the organism.

The relation between a material entity and its history is one-to-one. Histories are thus very special kinds of processes, since not only is it the case that, for any material entity *a*, there is exactly one process which is the history of *a*, but also is it the case that for every history there is exactly one material entity which it is the history of.

as(history\_of)[Elucidation: *b* **history\_of** *c* means: *c* is a *material entity* or *site* and *b* is the unique *history* of *c.* [XXX-001]

Axiom: if *b* **history\_of** *c* and *b* **history\_of** *d* then *c*=*d* [XXX-001]

Domain: history [XXX-001]

Range: material entity or site [XXX-001] ]

as(has\_history)[definition: *b* **has\_history** c iff *c* **history\_of** *b* [XXX-001]

]

Histories are additive. Thus:

Axiom: For any two *material entities* or *sites b* and *c*, the *history* of the sum of *b* and *c* is the sum of their *histories*.

### Process boundary

a(process boundary)[Definition: *p* is a *process boundary* =Def. *p* is a **temporal part** of a*process* & *p* has no**proper temporal parts.** [084-001]]

a(process boundary)[Axiom:Every process boundary **occupies\_temporal\_region** a*zero-dimensional temporal region.* [085-002] ]

a(process boundary)[Example: the boundary between the 2nd and 3rd year of your life. ]

### Relation of participation

a(has\_participant)[Elucidation**: has\_participant is an** instance-level relation between a *process*, a *continuant*, and a *temporal region* at which the continuant participates in some way in the *process*. [086-003]]

a(has\_participant)[Domain**:** process]

at(has\_participant)[Range**:** *independent continuant* that is not a *spatial region*, *specifically dependent continuant*, *generically dependent continuant*]

a(has\_participant)[Axiom: if *b* **has\_participant** *c***at** *t* then *b* is an *occurrent*. [087-001] ]

a(has\_participant)[Axiom: if *b* **has\_participant** *c***at** *t* then *c* is a *continuant*. [088-001] ]

a(has\_participant)[Axiom: if *b* **has\_participant** *c***at** *t* then *c* exists **at** *t*. [089-001] ]

a(has\_participant)[Axiom: if *b* **has\_participant** *c***at** *t* & *c* is a *specifically* *dependent continuant*, then there is some d, which is an *independent continuant* but which is not a *spatial region d*, and which is such that *c* **s-depends\_on** *d* **at** *t* & *b* **s-depends\_on** *d* **at** *t*. [090-003]

Axiom: if *p* **has\_participant** *c* **at** *t* & *c* is an *independent continuant* that is not a *spatial region*, then *p* **s-dependent** on *c* **at** *t.* [XXX-YYY] MAKE SURE THIS DOES NOT CONFLICT WITH ANYTHING ELSE ]

a(has\_participant)[Axiom: if *b* **has\_participant** *c***at** *t* & *c* is a *generically dependent continuant*, then there is some *independent continuant* that is not a *spatial region d*, and which is such that *c* **g-depends on** *d* **at** *t* & *b* **s-depends\_on** *d* **at** *t.* [091-003]

Axiom: *temporal* and *spatiotemporal regions* do not have **participants** [xxx-001] ]

Thus both specifically and generically dependent entities participate in processes – for example when a file is copied from one hard drive to another – but only *via* the bearers of their specifically dependent concretizations. +

note(spatial region,has\_participant)[Spatial regions do not participate in processes.]

On the participation of qualities in processes see the treatment of qualitative change, below.

## Qualities and processes as s-dependent entities

### The ontological square

BFO generalizes Zemach’s idea of a continuant entity by allowing not only *things* (such as pencils and people) as continuants, but also entities that are *dependent* on things, such as qualities, roles and dispositions. BFO thereby draws not merely on Aristotle’s distinction between universals and particulars, but also on his division of substances and accidents, which reappears in BFO as the opposition between independent and dependent continuants.

#### Determinable and Determinate Quality Universals

Qualities, in BFO, are entities in their own right (of the sort referred to elsewhere in the literature as tropes, or individual accidents). They are entities which are dependent on the independent continuant entities (such as planets, organisms, molecules) which are their bearers.

Qualities instantiate quality universals, which are divided into *determinable* (such as *temperature*, *length* and *mass*) and *determinate* (such as: 37.0°C *temperature*, 1.6 meter *length*, and 4 kg *mass*). (Anticipating our discussion of ‘process profile universals’ later in this document, we might refer to determinate quality universals as quality profiles.) [84]

Determinable quality universals are *rigid*, in the sense that, if a determinable quality universal is exemplified by a particular bearer at any time during which this bearer exists, then it is exemplified at every such time. John’s temperature (a certain quality instance inhering in John from the beginning to the end of his existence) instantiates the same determinable universal *temperature* from the beginning to the end of John’s existence. Determinate quality universals, on the other hand, are non-rigid: the same quality instance may instantiate different determinate universals at different times, as in Figure 8. A parallel distinction between determinable and determinate universals applies also to realizable entities.



Figure : John's temperature and some of the determinable and determinate universals it instantiates at different times

We note in passing that the determinate temperature universals are independent of whatever system of units is used to describe them. The universals here referred to in terms of degrees Celsius would be instantiated even in a world in which a system of units for measuring temperature had never been established.

We note further that, if temperature changes continuously, then it follows that there are uncountably many determinate temperature universals, and similarly for other types of continuous change.

When clinicians speak for example of John’s temperature as falling within some ‘normal’ range, then they are referring to the determinate qualities inhering in John, but they are describing them in relation to the corresponding qualities inhering in other persons in the same reference group. A single person has a normal temperature only relative to (the temperature qualities of) persons in one or other larger population (for example healthy persons at rest in an indoor environment, persons recovering from pneumonia, and so on).

Because processes are extended in time, this means that, for each process, we can identify arbitrarily many sub-processes, temporal parts, occupying sub-intervals of the temporal interval occupied by the process as a whole.

The assertion that one entity is an occurrent part of a second entity means simply that both are occurrents and that the first is a part of the second. The sum of processes taking place in your upper body during the course of your life is a proper continuant part of the sum of all processes taking place in your whole body during the same interval of time. There is however a narrower relation which holds between one *occurrent* and another when the former is exactly the restriction of the latter to a *temporal region* that is a **proper part** of the *temporal region* occupied by the latter. What it is for one entity to be a **temporal part** of a second entity is defined above.

### The problem of process measurement data

Process measurements, and processes of measurement, and measurement data, do not, strictly speaking, fall within the province of a formal ontology such as BFO. However, it is of value to explore what happens when BFO is used to annotate the results of measurements of qualities. In a typical case on the side of continuants, for example the measurement of your height, the following elements can be distinguished:

1. the BFO:*object* that is you,
2. the BFO:*determinable quality* that is your height throughout your life,
3. the BFO:*determinate quality* that is your height **at** *t*,
4. the BFO:*one-dimensional spatial region* that is the distance from the top of your head to the base of your feet that is measured **at** *t* when we measure your height **at** *t*.

The result of this measurement is referred to by means of

1. the IAO:*scalar measurement datum*: ‘1.7 m tall **at** *t*’.

Each item on this list is unproblematically identifiable as instantiating a BFO category. (4) is an data item, for instance a record in some file on your laptop. The data item is said to be ‘generically dependent’ upon its bearer, since it can be transferred to another laptop through a process of exact copying. The temperature of your laptop, in contrast, is specifically dependent on the laptop, since the temperature of a material entity (the temperature trope, this specific instance of the universal *temperature*), cannot migrate from one material entity to another.

When attempts were made to develop a corresponding analysis in BFO terms of the data resulting from measurements of processes, however, then a problem arises. In the case of a body moving with constant speed, for example, we can here distinguish at least the following elements:

1. the BFO:object that is moving,
2. the BFO:process of moving,
3. the BFO:temporal region occupied by this process,
4. the BFO:spatiotemporal region occupied by this process (path of the motion),
5. the speed of the process at some temporal instant *t*,

where (5) is referred to by means of

1. the IAO:scalar measurement datum: ‘3.12 meters per second **at** *t*’.

### Why processes do not change

Each of items (1)-(4) and (6) instantiates a readily identifiable BFO category. Item (5), on the other hand, presents a problem, since the obvious candidate category of *process quality*, a counterpart on the occurrent side of BFO:*quality* on the side of continuants, is not recognized by BFO. To see why not, consider the following scenario, which is designed to illustrate the contrasting logico-ontological orders governing the continuant and occurrent realms as BFO conceives them [14].

Imagine, first, John, a BFO:*object*, who, on a certain day, either does or does not go on a one-month diet. In the former case John’s determinable weight quality will decrease; in the latter case this quality will remain constant. In either case John will remain at the end of the month *the same object* as he was on the day in question. Both John and his weight are first class entities, thus instantiating universals (*person* and *weight*, respectively) represented in corresponding BFO-conformant ontologies.

In the case of a process – for example John’s *life* – in contrast, no parallel scenario is imaginable. Of course we can imagine John’s lifeas varying under two different scenarios – *life with diet*; *life without diet*. But then, however small the variation from one imagined life to another, we are here imagining two different lives.

As Galton and Mizoguchi point out [53], persuasive arguments have been presented in the literature to the effect that processes cannot change, because processes *are* changes (they are changes in those continuant entities which are their participants). Certainly we have ways of speaking whose surface grammar suggests that processes can change. But when we say, for example, *let’s speed up this process*, then what we mean is: let’s ensure that some on-going process is one which will be quicker than the process that would have occurred had we not made some specific extra effort.

Because independent continuants may gain and lose parts over time, the instance-level parthood relation on the side of continuants is *indexed by time*. The instance-level parthood relation on the side of occurrents, in contrast, holds always in a non-indexed way. Certainly a process can have as successive temporal parts subprocesses which differ in manifold ways. But it is here the participants in the process that change – and these participants are in every case continuants.

Some continuant universals, such as *larva* or *fetus* are non-rigid, in the sense that if some organism *b* instantiates the universal *larva* **at** *t*, then it does not follow that *b* instantiates*larva* at all times at which *b* exists. Universals on the side of occurrents, in contrast, are always rigid, so that if an occurrent instantiates a universal at some time, then it instantiates this universal at all times. [16] This is because, while continuants can change their type from one time to the next (as when an embryo becomes a fetus, which in turn becomes an infant [13]), no similar sort of change can be identified on the side of occurrents.

### First approximation to a solution of the problem of process measurement data

The problem lies properly in the coverage domain of IAO. Yet it needs to be dealt with here, since it gets to the heart of one seeming shortcoming of the BFO framework.

Suppose a given process of running is described as increasing speed continuously over a certain interval of time. It is then more precisely the moving body that is changing, and not the process in which that body participates. Now we can of course talk as if given, say, a running with speed *v*, then there is some attribute of this process in addition to the running itself – namely the attribute that it is a process *of increasing speed*. And if BFO is to serve the needs of scientists in providing the basis for common vocabularies to be used in annotating measurement information, then it is essential that BFO provides some simple means for annotating attributions of this sort on the side of occurrents, just as it provides the means to annotate measurements and other of qualities to objects on the side of continuants.

Our argument is that, for occurrents, such attributions are *just a way of speaking:* there is no extra first-class entity, *in addition to the running process itself*, which makes them true. How, then, do we respond to the need on the part of the users of BFO to annotate data deriving from measurement and other attributions which have processes as their targets? How, for example, do we understand the reference of expressions such as: asserting that a certain motion ‘has speed 3.12 m/s’? In sum, our answer is that an assertion of the given sort states not that that the process in question *has some special quality* (which the same process, in another scenario, might have lacked); rather, we are asserting that this process *is of a certain special type*. Thus an assertion to the effect that

1. motion *p* has speed *v* **at***t*

is analogous, not to:

1. rabbit *r* has weight *w* **at** *t*,

but rather to:

1. rabbit *r* **instance\_of** universal *rabbit* **at** *t.*

(1), in other words, should be interpreted as being of the form:

(4) motion *p* **instance\_of** universal: *motion with speed v* **at** *t.*

This treatment of attribution in terms of instantiation reflects standard policy throughout the BFO ontology – part of a strategy to maintain BFO’s ontological and logical simplicity. There are no qualities of occurrents, in BFO, just as there are no qualities of qualities, and also no qualities of spatial or temporal regions. Leaving aside the single case of qualities of independent continuants, attributions in BFO are quite generally treated in terms of the relation of instantiation, as in Table 1:

|  |  |
| --- | --- |
| spatial region *r* has volume *w* | *r* **instance\_of** universal *spatial region with volume w* |
| volume quality *q* has value 2 cubic meters **at** t | bearer of *q* exactly located in *spatial region* *r* and *r* **instance\_of** universal *1 cubic meter spatial region* |
| temporal region *t* has duration *d* | *t* **instance\_of** universal *temporal region with duration d* |
| process *p* has duration *d* | process *p* occupies temporal region *t* and *t* **instance\_of** universal *temporal region with duration d* |
| temperature quality *q* has value 63° Celsius | *q* **instance\_of** universal 63° Celsius *temperature quality* |

Table : Examples of attributions in BFO

## Processes as dependent entities

Processes themselves stand to the independent continuants which are their participants as qualities stand to the independent continuants which are their bearers. Our strategy is to use the instantiation relation between process instances and process universals as basis for an account of how process attributions (veridical process attribution talk) relate to the underlying reality. To make an approach along these lines work, however, we will need to find a way to do justice to the fact that the processes with which experimenters have to deal are typically highly complex in nature. A running process, for example, might simultaneously make true assertions to the effect that it is an instance not merely of the determinable universal *running process* and of a variety of further determinable universals such as

* constant speed running process
* cardiovascular exercise process
* air-displacement process
* compression sock testing process

but also of a much larger variety of determinate universals such as

*running process* of 30 minute duration

*running process* in the direction: due North

3.12 m/s *motion process*

9.2 calories per minute *energy burning process*

30.12 liters per kilometer *oxygen utilizing process*

and so on.

That processes involve change is then reflected in the fact that the determinate universals listed here are non-rigid; thus John’s process of running may be a 9.2 calories per minute energy burning process at one time and an 8.7 calories per minute energy burning process at another.

### An Amended Proposal

To see what is involved here, consider

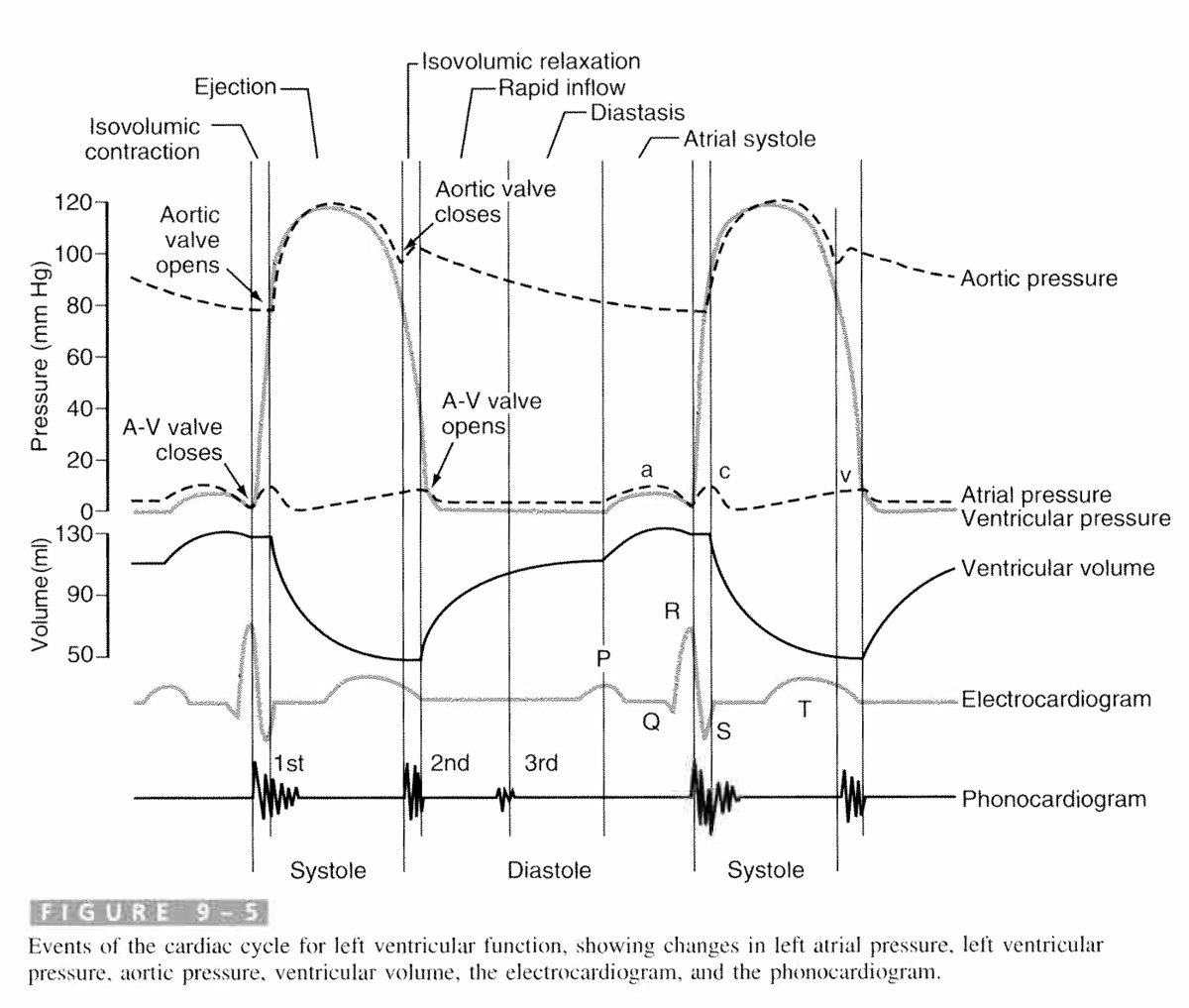


Figure 9, which illustrates the cardiac events occurring in the left ventricle in a single beating of a human heart. This figure tells us that each successive beating of the heart is such as to involve (at least) six different sorts of physiological processes, corresponding to measurements along the six distinct dimensions of *aortic pressure*, *atrial pressure*, *ventricular pressure*, *ventricular volume*, *electrical activity*, and *voltage*, respectively. (Here voltage is used as a proxy for the intensity of sound.) As de Bono, *et al*., point out, these measurements reflect the variables encoded in models of human physiology created by scientists using ordinary differential equations [85].

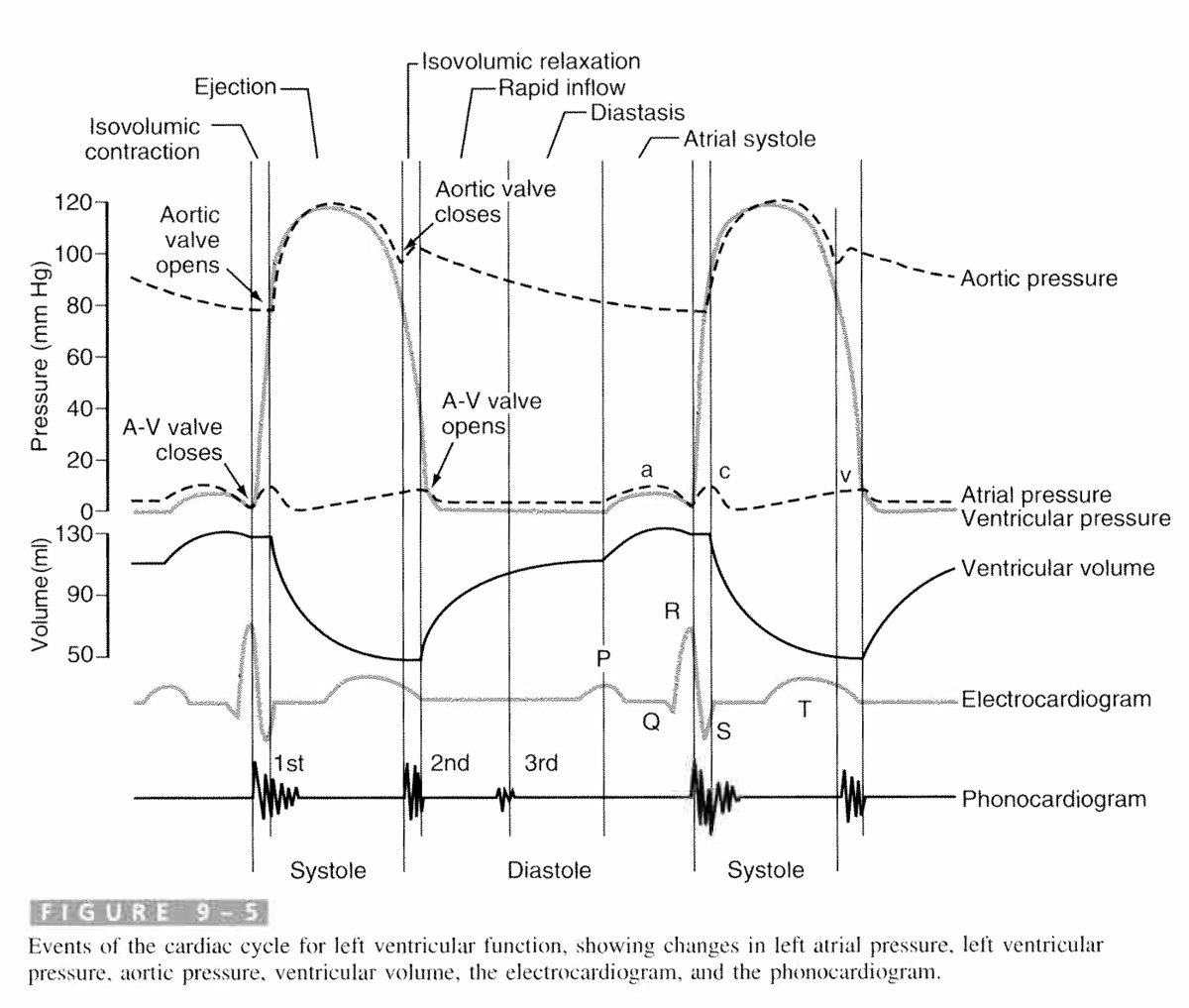


Figure 9. A Wiggers diagram (from Guyton, *Medical Physiology*)depicting: Events of the cardiac cycle for left ventricular function, showing changes in left atrial pressure, left ventricular pressure, aortic pressure, ventricular volume, the electrocardiogram, and the phonocardiogram.

The Figure illustrates how, when measuring activity in a complex system such as a human organism, it is variations only along specific structural dimensionsof the corresponding whole process to which our measuring processes and the resultant measurement data relate. Other dimensions can be added to those depicted in the Figure, such as the dimensions of change in volume and shape of the chambers, which manifest obvious interdependences. In the *running* case, different measuring processes are directed to structural dimensions within the whole process pertaining to *speed of motion*, *energy consumed*, *oxygen utilized*, and so forth*.* In each case we focus on some one structural dimension and ignore, or strip away in a process of selective abstraction, all other dimensions within the whole process.

When we measure processes, we employ selective cognition to focus on certain partial processes within the measured process as a whole. In the simplest possible case, such selective cognition will focus on sequences or series of *qualities* –one simple example of what, in what follows, we shall call *process profiles*, the referents of expressions such as ‘this is what John’s temperature did overnight’ while pointing to John’s temperature chart. When we measure, for example, the *process of temperature increase* in patient John, then John himself is the bearer of the temperature qualities that we measure and record on John’s temperature chart. And when we measure John’s growth process by taking measurements of his height and weight at regular intervals, then there, too, it is John who is the bearer of the qualities that we measure and record. Process profiles of this simple sort can be represented by means of a graph in which measures of a certain quality are plotted against time. (We will address in a later version of BFO the complexities that arise when we take account of phenomena such as averaging, interpolation and measurement error typically involved in the process leading to the creation of such graphs.)

#### Mutual dependence among qualities and their parts

When we measure continuants, too, there is a similar process of selective abstraction, which yields – again in the simplest possible case – representations of *qualities* of height, mass, and so on. Here, too, there isa counterpart of the Wiggers diagram illustrated in Figure 9, which arises for example in the realm of color qualities in virtue of the fact that we can distinguish, when measuring colors, between three dimensions of variation, corresponding to three mutually s-dependent parts of hue, brightness and saturation which can be measured independently. An instance of color‑hue cannot of its nature exist, except as bound up with some instance of brightness and saturation; instances of brightness and saturation, similarly, cannot exist except as bound up with some specific instance of color hue [45]. This yields a dependence structure of the sort depicted in Figure 10. [3, 20]



Figure 10: Three-sided mutual dependence of the three instance-level parts (*a*, *b*, *c*) of a color instance: *hue* (α), *brightness* (β) and *saturation* (γ).

The parts represented in this Figure can be, again, separated out by the observer through a process of selective attention – as when we measure the saturation of a color sample and ignore its hue and brightness – but they cannot exist except in the context of some whole of the given sort.

## Process profiles

We can identify analogous dependence relations among processes and their parts of a variety of different sorts. When a key is used to open a lock, for example, then the movement of key and lock form a mutually dependent process pair, and something similar holds when a pair of boxers are sparring in the ring, or a pair of rumba dancers are moving together across the dance floor.

For many families of processes, for example of human metabolism or physiology, researchers have identified complex repertoires of process profile universals. It is instances of such universals that are represented in many of the assertions clinicians make when reporting process measurements by using charts of, for example, temperature, respiration or pulse rate. (See the [Vital Sign Ontology](http://www.acsu.buffalo.edu/~ag33/vso.html) for further details.)

We introduce, first, the relation **process\_profile\_of** between one process and another surrounding process, as a special sort of **occurrent parthood** relation, which we elucidate as follows:

a(process profile)[Elucidation: *b* process\_profile\_of*c* holds when

*b* **proper\_occurrent\_part\_of** *c*

& there is some **proper\_occurrent\_part** *d* of *c* which

has no parts in common with *b*   
& is mutually dependent on *b*& is such that *b*, *c* and *d* occupythe same **temporal region** [094-005]]

We can now define *process profile* as follows:

as(process profile)[Definition: *b* is a *process\_profile* =Def. there is some process *c* such that *b* **process\_profile\_of** *c* [093-002]]

A special subtype of such mutual dependence among process parts arises in cases such as are illustrated in

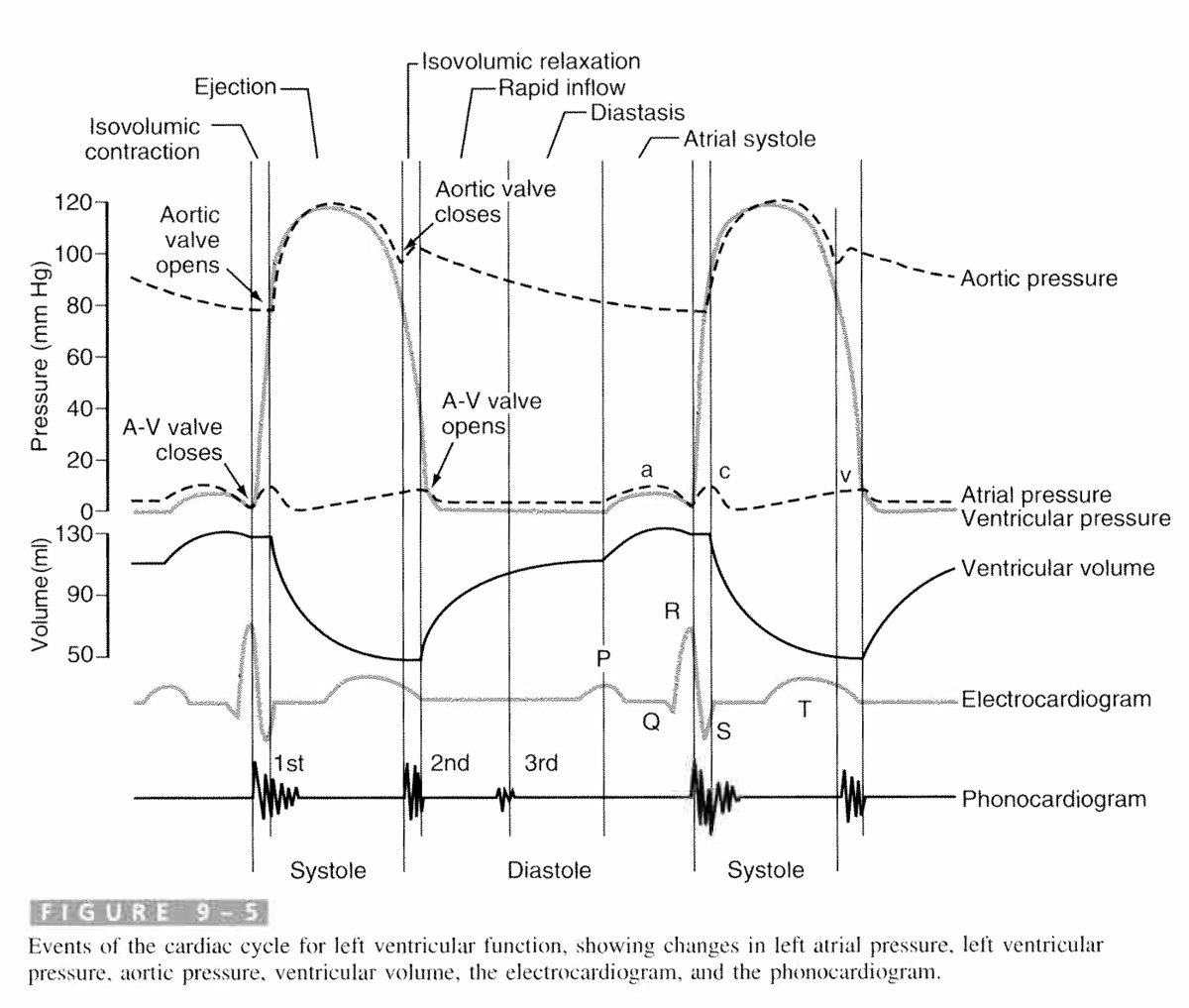


Figure 9, where the **process profile parts** in question are of the sort that serve as the target of a process of measurement. The key to understanding how many sorts of process measurement data are to be annotated in BFO terms is to identify the process profiles represented by the corresponding measurement charts created in the salient domains.

When John is exercising and at the same time John is participating in a compression sock testing process, then the process profile which is John’s performance of the test is mutually dependent on the process profile which is John’s exercising. When heat is applied to a volume of gas in a closed container then the pressure of the gas will rise; when we measure the rise in temperature and in pressure of the gas then in each case we rely on selective abstraction, which enables us to identify and measure two distinct process profile parts of a single whole process. Here the process profiles involved are: *increase in pressure of gas* and *increase in temperature of gas*, respectively.

Of course these process profiles are in some sense manifestations of the same phenomenon – the increase in average kinetic energy of the gas molecules – they are parts (streaks, strands, …) within this phenomenon, upon which cognition is focused when the corresponding measurements are taken.

### Quality process profiles

Example(process profile)[The simplest type of process profiles are what we shall call ‘quality process profiles’, which are the process profiles which serve as the foci of the sort of selective abstraction that is involved when measurements are made of changes in single qualities, as illustrated, for example, by process profiles of mass, temperature, aortic pressure, and so on. ]

### Rate process profiles

example(process profile)[On a somewhat higher level of complexity are what we shall call *rate process profiles*, which are the targets of selective abstraction focused not on determinate quality magnitudes plotted over time, but rather on certain ratios between these magnitudes and elapsed times. A speed process profile, for example, is represented by a graph plotting against time the ratio of distance covered per unit of time. Since rates may change, and since such changes, too, may have rates of change, we have to deal here with a hierarchy of process profile universals at successive levels], including:

|  |
| --- |
| speed profile  constant speed profile  2 mph constant speed profile  3 mph constant speed profile  increasing speed profile  acceleration profile  constant acceleration profile  32ft/s2 acceleration profile  33 ft/s2 acceleration profile  variable acceleration profile  increasing acceleration profile |

and so on. We might also add a dichotomy between scalar and vector process profiles. We could then conceive a speed profile, for example, as a scalar profile which is a constant ratio of a distance travelled per unit of team. We might treat *vector process profile*, as a subtype of speed profile which incorporates the direction of motion. Similarly under *acceleration profile* we could include subtypes such as *centripetal acceleration profile* (for acceleration along a curved path), *linear acceleration profile* (for acceleration along a straight line), and so on.

Clearly, the types and subtypes listed here are analogous to the determinable and determinable types and subtypes of qualities recognized by BFO-conformant ontologies on the continuant side discussed already above. Here again the reader must bear in mind that in both sets of examples the determinate universals in question, while they need to be referred to using specific units of measure, are in fact unit-specification independent. We shall see, however, that the way we address the issue of rigidity and non-rigidity of such universals differs from what was the case when dealing with continuants.

### Beat process profiles

Example(process profile)[One important sub-family of rate process profiles is illustrated by the beat or frequency profiles of cyclical processes, illustrated by the 60 beats per minute beating process of John’s heart.

Each such process includes what we shall call a beat process profile instance as part, a subtype of rate process profile in which the salient ratio is not distance covered (as in the case of speed) but rather number of beat cycles per unit of time. Each beat process profile instance instantiates the determinable universal *beat process profile.* But it also instantiates multiple more specialized universals at lower levels of generality, selected from

rate process profile

beat process profile

regular beat process profile

3 bpm beat process profile

4 bpm beat process profile

irregular beat process profile

increasing beat process profile

and so on.

In the case of a regular beat process profile, a rate can be assigned in the simplest possible fashion by dividing the number of cycles by the length of the temporal region occupied by the beating process profile as a whole. Irregular process profiles are process profiles where an analysis of this sort is inadequate Such irregular process profiles, for example as identified in the clinic, or in the readings on an aircraft instrument panel, are often of diagnostic significance.]

In the case of rate process profiles in general, measurement data are often expressed not in terms of the process profile instantiated across a temporal interval, but rather of what holds at some specific temporal instant. The latter is then defined in terms of the former in the following way (continuing our list in section 3.11.4):

(5) John is moving with speed *v* **at** time instant *t*

(5) asserts, in first approximation, that there is some temporal interval (*t*1, *t*2), including *t* in its interior, in which the speed *v* process profile is instantiated. More precisely (in order to take account of the fact that John may be moving with a continuously changing speed in the neighborhood of *t*), (5) must be formulated in something like the following terms:

(6) Given any ε, however small, we can find some interval (*t*1, *t*2), including *t* in its interior, during which the speed *w* **at** which John is moving is such that the difference between *w* and *v* is less than ε.

Note that the logical significance of the ‘**at** time instant *t*’ in (5) is distinct from what it is, for example, in

1. John has temperature 64° Celsius **at** time instant *t*

In (7), we are using ‘**at** *t*’ as part of an assertion concerning the instantation by an individual of a continuant universal; in (5), we are using ‘**at** *t*’ to pick out a part of a process which instantiates an occurrent universal – where the instantiation relation itself is (as it were) timeless. The determinate continuant universal involved in (7), namely: *temperature of* 64° *Celsius*, is non-rigid, because John’s temperature can instantiate different such determinate universals at different times. The determinate occurrent universal involved in (5), namely: *motion with speed v* are non-rigid in the sense that, while a given motion instantiates all the occurrent universals that it instantiates timeless, it can appear that one and the same motion instantiates different such determinate universals at different times because it has different parts which unfold successively in time. To say that a single motion *m* can be now quicker now slower is not to make a statement analogous to: John can be now warmer, now colder. Rather it is to make a statement of the form: *m* has two parts, a slow one and a quick one.

## Spatiotemporal region

a(spatiotemporal region)[Elucidation: A *spatiotemporal region* is an *occurrent* entity that is **occurrent\_part** of spacetime. [095-002]]

‘Spacetime’ here refers to the maximal instance of the universal *spatiotemporal region.*

Spatiotemporal regions are such that they can be **occupied\_by** processes.

as(spatiotemporal region)[Examples: the *spatiotemporal region* **occupied** by a human life\, the *spatiotemporal region* **occupied** by the development of a cancer tumor\, the *spatiotemporal region* **occupied** by a *process* of cellular meiosis. ]

a(spatiotemporal region)[Axiom: All **occurrent\_parts** of *spatiotemporal regions* are *spatiotemporal regions*. [096-002] ]

a(spatiotemporal region)[Axiom: Each spatiotemporal region **projects\_onto** some temporal region. [098-001] ]

a(spatiotemporal region)[Axiom: Each spatiotemporal region at any time *t* **projects\_onto** somespatial region **at** *t*. [099-001] ]

The projection relation will need to be defined in each case in terms of the frame employed.

a(spatiotemporal region)[Axiom: Every *spatiotemporal region* *s* is such that *s* **occupies\_spatiotemporal\_region** *s.* [107-002]

Every *spatiotemporal* *region* **occupies\_spatiotemporal\_region** itself.]

as(occurrent)[Axiom: Every *occurrent* **occupies\_spatiotemporal\_region** some **spatiotemporal region.** [108-001]]

## Temporal region

Given a temporal reference frame R, we can define ‘timeR’ as the maximal **instance** of the universal *temporal region*.

a(temporal region)[Elucidation: A *temporal region* is an *occurrent* entity that is **occurrent\_part** of time as defined relative to some reference frame. [100-002]]

a(temporal region)[Axiom: Every *temporal region* *t* is such that *t* **occupies\_temporal\_region** *t.* [119-002] ]

a(temporal region)[Axiom: All **occurrent\_parts** of *temporal regions* are *temporal regions*. [101-002] ]

From axiom [???-???] NEEDS TO BE ADDED we can infer that no entity is ever **continuant\_part** of any *occurrent*, and no entity is every **occurrent\_part** of any *continuant*.

A temporal region is an *occurrent entity* upon which a process can be projected. Temporal regions are introduced in BFO to provide a basis for consistent representation of temporal data, for example as described in [68].

#### Zero-dimensional temporal region

a(zero-dimensional temporal region)[Elucidation: A *zero-dimensional temporal region* is a temporal region that is without extent. [102-001]]

as(zero-dimensional temporal region)[Examples: a temporal region that is occupied by a process boundary\; right now\; the moment at which a finger is detached in an industrial accident\; the moment at which a child is born\, the moment of death. ]

a(zero-dimensional temporal region)[Synonym: temporal instant. ]

#### One-dimensional temporal region

a(one-dimensional temporal region)[Elucidation: A *one-dimensional temporal region* is a temporal region that is extended in time. [103-001]]

a(one-dimensional temporal region)[Example: The temporal region during which a process occurs. ]

note(*one-dimensional temporal region*)[A temporal interval is a special kind of *one-dimensional temporal region*, namely one that is self-connected (is without gaps or breaks).]

### The precedes relation

**Preceded\_by**, defined in RO, is not defined in the BFO2 Reference, except by citation to a paper. That paper does not provide axioms on the relation. The RO definition from [http://obofoundry.org/ro/](http://obofoundry.org/ro/" \t "_blank) is given below.

As there is an open issue regarding the OWL rendering this should be fixed in the reference.

The RO page definition is suboptimal as the quantification and type of t (instant, interval) isn't stated.

[http://krr.meraka.org.za/~aow2010/Trentelman-etal.pdf](http://krr.meraka.org.za/~aow2010/Trentelman-etal.pdf" \t "_blank) offers:

Relation of **preceded\_by**

From [16]:

From [16]:

*t* **first\_instant** *p* = Def. *p* **occurring at** *t* & *t* is a *zero-dimensional temporal region* & for all *t′*, if *t′* **earlier** *t*, then not *p* **occurring at** *t′* [XXX-001]

*t* **last\_instant** *p =* Def. *p* **occurring at** *t* & *t* is a *zero-dimensional temporal region* & for all *t′*, if *t* ***earlier*** *t′,* then not *p* ***occurring at*** *t′* [XXX-001]

*p* **preceded\_by** *p′ =* Def. *p* and *p′* are *processes* & the last temporal instant of *p* is earlier than the first temporal instant of *p′* [XXX-001]

*p* **immediately\_preceded\_by** *p′ =* Def. *p* **preceded\_by** *p′* & there exists a *temporal instant* *t* which is both the first instant of *p* and the last instant of *p′*. [XXX-001]

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| --- |
|  |

**BFO Relations**

Need to deal with all the RO relations

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# Appendix I Summary of most important changes in BFO 2.0 as compared to BFO 1.1

### Clarification of BFO:*object*

The document emphasizes that the categories note(material entity)[Object, Fiat Object Part and Object Aggregate are not intended to be exhaustive of Material Entity. Users are invited to propose new subcategories of Material Entity.]

The document provides a more extensive account of what 'Object' means (roughly: note(object)[an object is a maximal causally unified material entity]); it offers three paradigms of causal unity (for example(object)[cells and organisms], for example(object)[solid portions of matter], and for example(object)[engineered artifacts])

### Introduction of mutual dependence

The document recognizes cases where multiple entities are mutually dependent on each other, for example between color hue, saturation and brightness; such cases can also involve mutual generic dependence as in the case of a disposition of a key to open either this or some equivalent lock, and of the lock to be opened by this or some equivalent key (for example a copy made using a template derived from the original key, or on the basis of some formula or blueprint).

### New simplified treatment of boundaries and regions

note(continuant fiat boundary)[In BFO 1.1 the assumption was made that the external surface of a material entity such as a cell could be treated as if it were a boundary in the mathematical sense. The new document rests on the view that when we talk about external surfaces of material objects in this way then we are talking about something fiat. In a future version of BFO we will deal more extensively with boundaries, including also a treatment of boundaries at different levels of granularity.

More generally, the focus in discussion of boundaries in BFO 2.0 is now on fiat boundaries, which means: boundaries for which there is no assumption that they coincide with physical discontinuities. The ontology of boundaries hereby becomes more closely allied with the ontology of regions.]

#### Revision of treatment of spatial location

We generalize the treatment of **located\_in** and remove the relation **contained\_in**.

#### Treatment of process predications under the heading ‘process profiles’

The document introduces the idea of a process profile to provide a means to deal with certain sorts of process measurement data. To assert, for example, that a given heart beating process is a 72 beats per minute process, is not to ascribe a quality to the process, but rather to assert that there is a certain structural part of the process, called a ‘beat profile’, which instantiates what we shall call a determinate process universal.

#### Inclusion of relations as part of BFO vs. RO, with changes to relations

#### New relation exists\_at added.

To say that *b* **exists\_at** *t* means: *b* is an entity which exists at some temporal region *t*, as for example when a fetus develops or a football match occurs during some given temporal interval.

#### Relations of parthood disambiguated

Hitherto BFO has distinguished parthood between continuants and occurrents by means of the‘**at** *t*’ suffix used for the former; henceforth we will use the explicit distinction between **continuant\_part\_of** and **occurrent\_part\_of** (still using the ‘**at** *t*’ suffix for the former).

#### Revision of treatment of process

‘Processual entity’ is eliminated, and ‘process’ is given a more general meaning, to make it the equivalent, on the side of occurrents, of ‘material entity’ on the side of continuants.

### Future directions

* Treatment of frame-dependence of regions of space, of regions of time, and of certain qualities such as mass and spatial qualities.
* Introduction of **boundary\_of** (including **fiat\_boundary\_of**) relations, and of a treatment of dimensionality.
* Treatment of type-level relations; rules for quantifying over universals.
* More detailed treatment of two kinds of causal relations (1) causal dependence, for example the mutual causal dependence between the pressure and temperature of a portion of gas; (2) causal triggering, where a process is the trigger for a second process which is the realization of a disposition.
* Physics terms such as ‘force’, ‘momentum’, ‘inertia’, ‘frame of reference’.
* Relation of dependence of objects on qualities (e.g. of you on your mass)