Systems Engineering Research Center
Presents:

ONTOLOGY BOOTCAMP
Introduction to Ontology for Systems Engineers

Instructor: Dr. Barry Smith,
SUNY Distinguished Professor of Philosophy and
Julian Park Chair,
University of Buffalo
<table>
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<tr>
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<tr>
<td>8:00 AM</td>
<td>Registration &amp; Breakfast</td>
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| 8:30 AM | **Introduction and Background: Semantic Technology for Systems Engineering**  
Ontology Timeline  
1: 1970s–Strong AI, Robotics, PSL  
2: 1990s– The Semantic Web, Linked Open Data  
3: 2000s– Lessons from the Human Genome Project |
| 9:15 AM | **Ontology Suites**  
Open Biomedical Ontologies (OBO) Foundry  
SWEET, and other domain ontology suites  
Joint Doctrine Ontology  
Common Core Ontologies (CCO)  
Principles for Ontology Building  
Toy Example. Military Vehicle Ontology |
| 10:15 AM| Coffee                                                               |
| 10:30 AM| Future-Proofing Ontologies: The Case of the Gene Ontology  
Building ontologies with Basic Formal Ontology  
Industrial Ontologies Foundry (IOF)  
A BFO-based ontology for materials science  
Relations in BFO  
Realizables in BFO  
Roles  
Dispositions |
| 12:30 PM| Lunch                                                                |
| 1:15 PM | **Example Ontology from the SE Domain**  
Functions  
Capabilities  
BFO-based Ontology for Information Entities  
AFRL Digital Thread/Digital Twin  
Product Life Cycle (PLC) Ontology  
Commodities, Services and Infrastructure |
| 3:00 PM | Break                                                                |
| 3:15 PM | **Interactive session: Defining `system`**                           |
| 4:30 PM | Adjourn                                                              |
Who am I?
Charter

The Semantic Technologies Foundation for Systems Engineering is to promote and champion the development and utilization of ontologies and semantic technologies to support system engineering practice, education, and research.
Specifically, The Foundation Will

• Work to build consensus around principled, rigorous use of systems engineering language
  – Not just capturing current usage, but proposing normalized usage that entails semantic rigor
• Capture and formalize this consensus in formal ontologies using well-established languages and techniques from Knowledge Representation
• Collect and promulgate methodological guidance for development of related ontologies from industry and academia
• ...
Initial Core team members of ST4SE

- Steve Jenkins  Jet Propulsion Lab
- David Long  INCOSE Past President and Vitech President
- Mark Blackburn  SERC Council Member
- Todd Schneider  Engineering Semantics
- Chris Paredis  Georgia Institute of Technology
- Hans Peter de Koning  European Space Agency
- Bill Schindel  INCOSE MBSE Patterns Working Group
- Henson Graves  Lockheed Martin Retiree
- Barry Smith (Consultant)  Director, National Center for Ontological Research
Introduction to Ontology

• **Ontology** = def. a representation of the types of entities in a given domain and of the relations between them.

• What is an ontology for? To promote interoperability across heterogeneous data systems

• How does it do this? By exploiting relative stability of natural language
[Example Ontology from SE Domain]
Ontology Timeline

1970—“Strong AI”: First-order logic formalizations of common-sense knowledge, PSL

1990–The Semantic Web, OWL, Linked Open Data

2005–The Age of Ontology Suites
Ontology Timeline 1: “Strong AI”: First-order logic formalizations of common-sense knowledge

1970: Robotics, Naïve Physics, First Order Logic
1980: KIF: Knowledge Interchange Format (Tom Gruber ... SIRI ... )
1984: Cyc (Doug Lenat)
1985: Naïve Physics Manifesto; Ontology of Liquids (Patrick Hayes)
~1995: First engineering ontologies
2003: Process Specification Language (PSL) Ontology (Michael Gruninger, then at NIST, now Toronto)
1995-2005 multiple ontologies of engineering created at NIST and elsewhere

A requirement ontology for engineering design
J Lin, MS Fox, T Bilgic - *Concurrent Engineering*, 1996

Ontology as a requirements engineering product
KK Breitman, JCS do Prado Leite - *Requirements Engineering* ..., 2003

Ontology-based active requirements engineering framework
SW Lee, RA Gandhi - ... *Engineering Conference*, 2005

...
Process Specification Language (PSL) ~2003

Top level of PSL Ontology built around:

- **Activity** = def. a class or type of action, such as *install part*, which is the class of actions in which parts are installed.
- **Activity-occurrence** = def. an event or action that takes place at a specific place and time, such as a specific instance of *install part* occurring at a specific timestamp.
- **Timepoint** = def. a point in time.
- **Object** = def. anything that is not a timepoint or an activity.

ISO 18629 from [TC 184/SC 4](https://www.iso.org/standard/18425.html) standards for industrial data.
ISO 15926: Industrial automation systems and integration—Integration of life-cycle data for process plants including oil and gas production facilities
Typical reasons for ontology failure, circa 2005

- No common methodology
- Short half life
- Approaches often tied to data modelling languages (UML, EXPRESS, …)
- Poor documentation (few definitions …)
- No standard language for use in ontology building

Consequence: very few real-world examples of successful use of ontologies in engineering
Ontology Timeline 2: The Semantic Web

1994: Tim Berners-Lee introduced “Semantic Web” at 1st WWW Conference
1994: Resource Description Framework (RDF)
1999: Protégé
2004: Web Ontology Language (OWL) 1.0
Consequence: ontology proliferation
2007: Linked Open Data
Linked Open Data 2009
Ontologies are worse than useless when built separately, each in its own way
Ontology is supposed to solve the problem of terminology bloat
Ontology Timeline 3: Lessons from biology

1990: Human Genome Project
1999: The Gene Ontology (GO)
2002: Open Biomedical Ontologies (OBO)
2002: Basic Formal Ontology (BFO)
2005: Age of ontology suites
The importance of the Gene Ontology (GO)

model organisms
each community has developed its own biological terminology
future proof an ontology = rise up to a higher level of generality
GO is an ontology for tagging genome data that is species neutral.
GO consists of three sub-ontologies

**Biological Process**
- biological process
- development
- pattern specification
- axis specification
- adaxial/abaxial pattern formation

**Molecular Function**
- molecular function
- binding
- nucleic acid binding
- DNA binding
- transcription regulator activity

**Cellular Component**
- cellular component
- organelle
- intracellular
- membrane-bound organelle
- intracellular membran-bound organelle
- cell
Perspective

Published online: 7 November 2007 | doi:10.1038/nbt1346

The OBO Foundry: coordinated evolution of ontologies to support biomedical data integration

Barry Smith¹, Michael Ashburner², Cornelius Rosse³, Jonathan Bard⁴, William Bug⁵, Werner Ceusters⁶, Louis J Goldberg⁷, Karen Eilbeck⁸, Amelia Ireland⁹, Christopher J Mungall¹⁰, The OBI Consortium¹¹, Neocles Leontis¹², Philippe Rocca-Serra⁹, Alan Ruttenberg¹³, Susanna-Assunta Sansone⁹, Richard H
Typical reasons for ontology failure, circa 2015

• Too many ontologies being built (people think it is easy to do)
• Too much redundancy between ontologies
• Too much inconsistency between ontologies
• Still no common methodology

But

• now we have a (mostly) accepted common language
• and we are beginning to see examples of widely acknowledged principles of best practice
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Ontology Suites
Best practice principles for ontology building
The core of these principles

• Start out from **domain-neutral top level** ontology
• Follow a hub-and-spokes approach: Create **suites** of consistently developed ontology modules, with suite-wide oversight to ensure non-redundancy between modules
• Rigorously enforce **reuse** of more general ontology content in more specific ontology resources (from reference ontologies to application ontologies)
Hub and spokes approach
ontologies are networked together and developed in coordination with each other. Terms in **spokes** ontologies are defined logically using terms from ontologies nearer the **hub**.
## Examples of ontology suites

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further examples of suite formation

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suites built following OBO Foundry principles

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JP 1-02

Capstone Pubs

Keystone Pubs
- Joint Personnel 1-0
- Joint Intelligence 2-0

Dictionary 1-02
- Legal Support 1-04
- Religious Affairs 1-06
- Joint & National Intel Supt to Military Ops 2-01

Doctrine Pubs
- Financial Management 1-08
- Joint Intel Prep of the Operational Environment 2-01.3
- CI and HUMINT Support 2-01.2
Goals of the Joint Doctrine Ontology (JDO) initiative

1. Create JDO, a computational counterpart of the DoD Dictionary of Military and Associated Terms (JP 1-02)

2. Test JDO in Air Force Research Lab (AFRL) and related initiatives to support joint operations

3. Use JDO to promote reuse of Joint Doctrine terminology in IT resources across DoD as part of a strategy to advance interoperability
JDO as computational shadow of JP 1-02

**Built for humans**

intratheater airlift — Airlift conducted within a the combatant commander or attached to a subord intertheater airlift. (JP 3-17)

intratheater patient movement — Moving pati command or in the continental United States. intertheater patient movement. (JP 4-02)

inventory control — That phase of military logis requirements determinations, procurement, c materiel. Also called inventory manag management; supply management. (JP 4-09)

inventory control point — An organizational unit of supply system that is assigned the primary r management of a group of items either for Department as a whole. Also called ICP. (JP 4-09)

ionizing radiation — Particulate (alpha, beta, and gamma) radiation of sufficient energy to displa (JP 3-11)

irregular warfare — A violent struggle among stat influence over the relevant population(s). Also
What is Joint Doctrine for?

• To achieve joint action
• Initially joint action = action involving live forces from more than one Service
• Increasingly joint action = action involving not only life forces but also automatic systems
Joint action requires interoperability of people and information systems

**Interoperability** = def. The ability of systems, units, or forces to provide data, information, materiel, and services to, and accept the same from, other systems, units, or forces, and to use the data, information, materiel, and services exchanged to enable them to operate effectively together.

DoD Instruction 8330.01
How is interoperability to be achieved?

DoD Instruction (DoDI) 8330.01:
By adherence to standards listed in the DoD IT Standards Registry (DISR).
How can we make the definitions of JP 1-02 serve as a benchmark of interoperability for military (IT) systems?

DoD requires that joint doctrine addresses the need for IT interoperability.

DoD does not require – and has no effective strategy to ensure – that the IT procedures themselves address the need for conformity with joint doctrine.

But such conformity is indispensable for unified action involving human warfighters and IT systems

and it would also bring benefits to military IT systems, including the Joint Doctrine Development System itself
The role of general categories

• JP 1-02 defines the

• standard US military and associated terminology to encompass the joint activity of the Armed Forces of the United States. These military and associated terms, together with their definitions, constitute approved Department of Defense (DOD) terminology for general use by all DOD components.

• (JP 1-02, Preface signed by Vice Admiral William E. Gortney, Director of the Joint Staff)
Importance of categories (Peter Morosoff)

• The purpose of military doctrine is to facilitate commanders and other warfighters in understanding the realities of war and their specific situations and then in accomplishing their missions.

• It achieves these ends largely through the identification and explanation of important general categories rather than of specific instances (such as a particular aircraft or IT system).

• Doctrine is in this sense re-usable; it is applicable to many different instances and to many different subkinds of the same general categories.

• This approach is effective because the basic realities of war are not changed by the fielding of new commanders, equipment, specialties, or tactics.
Joint Doctrine Ontology will use the language of joint doctrine

• JDO is in effect a shadow of JP 1-02, incrementally adding definitional enhancements and further elements of logical regimentation, but in such a way that the ontology and the dictionary which underlies it remain synchronized with each other through each successive revision of joint doctrine.
Joint Doctrine is authoritative

1. if conflicts arise between it and Service doctrine, then the former – absent more current and specific guidance from the Chairman of the Joint Chiefs of Staff – will take precedence.
2. that it is to be followed except when, in the judgment of the commander, exceptional circumstances dictate otherwise.
Joint Doctrine is logically authoritative

3. Terms used in Army doctrine to refer to Army-specific categories defined should be defined as subcategories of the corresponding Joint Doctrine category
Doctrine is authoritative during real warfighting

• Doctrine provides what we can think of as a common mental model – a shared frame of reference – which remains active through every phase of every military engagement.

• Doctrine provides the principles which determine how to understand the authorized command relationships and the authority that military commanders can use.

• It establishes common ways of accomplishing military tasks and facilitates readiness by promoting coordination in all aspects of training and planning.
### Examples of gaps in JP 1-02

<table>
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<th>Action</th>
<th>Nation</th>
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<td>Agent</td>
<td>National organization</td>
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<tr>
<td>Authority</td>
<td>Order</td>
</tr>
<tr>
<td>Commander</td>
<td>Organization</td>
</tr>
<tr>
<td>Geographical area</td>
<td>Territory</td>
</tr>
<tr>
<td>Geopolitical entity</td>
<td>Training</td>
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Step 1 for creating JDO as JP 1-02 shadow

Fill gaps with logically well-formed definitions tying JP 1-02 to Common Core Ontologies
Step 2 for creating JP 1-02 shadow

Remove logical errors in existing definitions (for example in definitions which confuse the entity you are defining with the term used to represent that entity):

**operational area** — An overarching term encompassing more descriptive terms (such as area of responsibility and joint operations area) for geographic areas in which military operations are conducted.
Step 3 for creating JP 1-02 shadow

Ensure that each term has exactly one definition
Disambiguate those terms in JP 1-02 which have multiple definitions

• **command** — 1. The authority that a commander in the armed forces lawfully exercises over subordinates by virtue of rank or assignment. 2. An order given by a commander; that is, the will of the commander expressed for the purpose of bringing about a particular action. 3. A unit or units, an organization, or an area under the command of one individual.
by replacing one term with multiple terms making the distinctions explicit

1. command authority
2. commander’s order (expressing the will of the commander)
3. command unit
Uses of JDO

• Better definitions
• Better Command and Control (C2)
• Netcentricity – discovery of data
• Outcomes research
• Facilitating DoD IT interoperability
• Facilitating unified action among IT developers.
  • today, even the best-intentioned IT developers must make assumptions on whether a warfighting term in a specification that is not listed in joint doctrine is valid as it is or has been superseded by more a current term
Joint Doctrine Ontology: A Benchmark for Military Information Systems Interoperability

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Abstract—When the U.S. conducts warfare, elements of a force are drawn from different Services and work together as a single team to accomplish an assigned mission on the basis of joint doctrine. To achieve such unified action, it is necessary that specific Service doctrines be both consistent with and subservient to joint doctrine. But there are two further requirements that flow from the ways in which unified action critical, if we are to prevent higher-level flaws cascading to domain-level doctrinal errors, that the terms of joint doctrine be defined correctly.

It is commonly supposed that doctrine provides not hard and fast rules but rather merely a loose and always revisable guide to action that is typically abandoned on first contact

http://ncor.buffalo.edu/2015/STIDS-JDO.pdf
suites built following OBO Foundry principles

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Benefits of modularity

- division of labor
- division of authority
- SME ownership
- owner motivation
- user motivation
- user discoverability
- support for incrementality
- reduces need for ‘mappings’
Examples of best practice principles

1. Distinguish *reference* ontologies from *application* ontologies
2. Reference ontologies built around one or more single-inheritance backbone taxonomies
   Single inheritance = every non-root node has exactly one parent
3. Create a suite of reference ontology modules which on any given level of generality do not overlap
4. Reference ontologies are asserted, application ontologies inferred
5. In a reference ontology: definitions of terms should be of the genus-species form

\[ B_1 \ldots = \text{species} \]

\[ B = \text{def. } A \text{ which } C \]

\[ A = \text{genus} \]

\[ C = \text{specific difference} \]
Application ontology (fragment)
6. Factor ontology content into normalized reference ontology modules wherever possible.

- **Object**: car
  - is_a: SUV, saloon car

- **Quality**: colour
  - is_a: blue, red
Toy example of reference ontology and application ontology for artillery vehicles
<table>
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<th>Reference Ontology Definitions</th>
<th>Application Ontology Definitions</th>
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<td><strong>artillery vehicle</strong> = def. vehicle designed for the transport of one or more artillery weapons</td>
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<td><strong>tractor</strong> = def: a vehicle that is used for towing</td>
<td><strong>Delta Battery artillery vehicle</strong> = def. an artillery vehicle that is at the disposal of Delta Battery</td>
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<td><strong>crane</strong> = def: a vehicle that is used for lifting and moving heavy objects</td>
<td><strong>Delta Battery artillery tractor</strong> = def. an artillery tractor that is at the disposal of Delta Battery</td>
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<td><strong>vehicle platform</strong> = def: means of providing mobility to a vehicle</td>
<td></td>
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<tr>
<td><strong>wheeled platform</strong> = def: a vehicle platform that provides mobility through the use of wheels</td>
<td></td>
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<tr>
<td><strong>tracked platform</strong> = def: a vehicle platform that provides mobility through the use of continuous tracks</td>
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Normalized reference ontologies

Types of Vehicle

1. Vehicle
2. Tractor
3. Wheeled Tractor
Normalized reference ontologies

Types of Vehicle

- Vehicle
  - Tractor
    - Wheeled Tractor

Maneuver, Fires and Effects (MFE) Branches and Functional Areas

- Fires Component
- Maneuver Component
  - Field Artillery Component
  - Armor Component
  - Infantry Component
  - Aviation Component
add relations as needed
create defined class: wheeled artillery tractor
add instances of classes as needed

Vehicle

Tractor

Wheeled Tractor

Fires Component

Field Artillery Component

Armor Component

Infantry Component

Aviation Component

used_by

instance_of

Delta Battery
use reasoner to *infer* application ontology of Delta Battery artillery vehicles

use of reference ontologies as starting point promotes interoperability across different branches and easy extendability

“Horizontal Integration of Warfighter Intelligence Data”
http://ontology.buffalo.edu smith/articles/Horizontal-integration.pdf
<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
</tr>
</thead>
</table>
| 10:30 AM | **Future-Proofing Ontologies: The Case of the Gene Ontology**  
Building ontologies with Basic Formal Ontology  
Industrial Ontologies Foundry (IOF)  
A BFO-based ontology for materials science  
**Relations in BFO**  
**Realizables in BFO**  
Roles  
Dispositions |
| 12:30 PM | Lunch |
| 1:15 PM  | **Example Ontology from the SE Domain**  
Functions  
Capabilities  
**BFO-based Ontology for Information Entities**  
AFRL Digital Thread/Digital Twin  
Product Life Cycle (PLC) Ontology  
Commodities, Services and Infrastructure |
| 3:00 PM  | Break |
| 3:15 PM  | **Interactive session: Defining 'system'** |
| 4:30 PM  | Adjourn |
Future proofing

The case of the Gene Ontology
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<td><strong>Cellular Component</strong> (FMA, GO)</td>
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<tr>
<td>MOLECULE</td>
<td>Molecule (ChEBI, SO, RnaO, PrO)</td>
<td><strong>Molecular Function</strong> (GO)</td>
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Yellow = Gene Ontology (1998–)
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~2005 suite begins to expand
## Environment Ontology (EnvO)

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<th>Occurrent</th>
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<td>Dependent</td>
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Recognizing a new family of protocol-driven processes (investigation, assay, clinical trial …)
recognizing information entities: data, publications, images, algorithms, engineering models, simulations, designs (led to BFO 2.0)
## Aboutness

<table>
<thead>
<tr>
<th>Independent Continuant (~THING))</th>
<th>Dependent Continuant (~Attribute)</th>
<th>Occurrent (~Process)</th>
<th>IAO</th>
<th>OBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient Demographics</td>
<td>Phenotype (Disease, …)</td>
<td>Disease processes</td>
<td>Data about diseases, … including image data …</td>
<td>Instruments, Biomaterials, Functions Parameters, Assay types, Statistics …</td>
</tr>
<tr>
<td>Anatomy</td>
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<td>Histology</td>
<td>Genotype (GO)</td>
<td>Biological processes (GO)</td>
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</tr>
<tr>
<td>Chemistry</td>
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</table>
if {future proofing = rising up to an ever higher level of generality} then what happens when we reach the top?
Aristotelian definitions

A = genus
B = def. A which Cs
B₁ ... = species
C = specific difference

example (from Aristotle):
human being = def. animal which is rational
Porphyry’s depiction of levels of more and less general universals in Aristotle

Supreme genus: SUBSTANCE
Differentiae: material immaterial

Subordinate genera: BODY SPIRIT
Differentiae: animate inanimate

Subordinate genera: LIVING THING MINERAL
Differentiae: sensitive insensitive

Proximate genera: ANIMAL PLANT
Differentiae: rational irrational

Species: HUMAN BEAST

Instances: Socrates Plato Aristotle …
GO’s three sub-ontologies
three most general universals (root nodes) in GO
three most general universals (categories)

BFO: Continuant

BFO: Independent Continuant

GO: cellular component

BFO: Dependent Continuant

GO: molecular function

BFO: Occurrent

GO: biological process
three most general universals (categories)

- BFO: Continuant
  - BFO: Independent Continuant
    - objects, parts of objects, collections of objects, systems, ...
  - BFO: Dependent Continuant
    - attributes: qualities, roles, functions, ...

- BFO: Occurrent
  - processes, beginnings, endings, missions, operations, ...
  - plumbing
independent continuants in the system realm

{ system designer
  system
  system operator
  system manager
}

independent continuant
occurrences in the systems realm

- building of system
- maintenance of system
- operation of system
rationale of OBO Foundry coverage = BFO
Building Ontologies with Basic Formal Ontology

By Robert Arp, Barry Smith and Andrew D. Spear

Overview
In the era of “big data,” science is increasingly information driven, and the potential for computers to store, manage, and integrate massive amounts of data has given rise to such new disciplinary fields as biomedical informatics. Applied ontology offers a strategy for the organization of scientific information in computer-tractable form, drawing on concepts not only from computer and information science but also from linguistics, logic, and philosophy. This book provides an introduction to the field of applied ontology that is of particular relevance to biomedicine, covering theoretical components of ontologies, best practices for ontology design, and examples of biomedical ontologies in use.

After defining an ontology as a representation of the types of entities in a given domain, the book distinguishes between different kinds of ontologies and taxonomies, and shows how applied ontology helps in solving problems of data visualization. It includes a case study of the BioPortal
BFO 2.0

Very small
Evolves very slowly
Strictly formal (a domain neutral, top-level) ontology
Active user forum
Large user base
~ 250 active projects using BFO
Benefits of shared top level

all the benefits of a shared standard, including:
• improved understandability of third-party content
• improved transportability of expertise
• telephone network effect
  – data annotated using BFO-conformant ontologies becomes more valuable
  – attracts more enterprises to adopt BFO
  – creates a virtuous cycle (snowball effect)
examples of suite formation following OBO Foundry principles, including use of BFO as hub

<table>
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Reference number of working WG2 N2363
Date: 2017-05-0108-28

Reference number of document: ISO/IEC 21838-2
Committee identification: ISO/IEC JTC1 SC32 WG2
SC32 Secretariat: US

Information technology — Ontologies —
Top-Level Ontologies (TLO) — Basic Formal Ontology (BFO)
Building Ontologies with Basic Formal Ontology

By Robert Arp, Barry Smith and Andrew D. Spear

Overview
In the era of “big data,” science is increasingly information driven, and the potential for computers to store, manage, and integrate massive amounts of data has given rise to such new disciplinary fields as biomedical informatics. Applied ontology offers a strategy for the organization of scientific information in computer-tractable form, drawing on concepts not only from computer and information science but also from linguistics, logic, and philosophy. This book provides an introduction to the field of applied ontology that is of particular relevance to biomedicine, covering theoretical components of ontologies, best practices for ontology design, and examples of biomedical ontologies in use.

After defining an ontology as a representation of the types of entities in a given domain, the book distinguishes between different kinds of ontologies and taxonomies, and shows how applied ontology is used to guide both: (1) the selection of entities for inclusion and exclusion; (2) the development of the kinds of relations to represent in the domain; and (3) the relevant constraints on the kinds of relationships.
~ 300 ontologies re-using BFO

ACGT Master Ontology (ACGT MO)
Alzheimer Disease Ontology (ADO)
Adverse Event Ontology (AEO)
Adverse Event Reporting Ontology (AERO)
AFO Foundational Ontology
Actionable Intelligence Retrieval System (AIRS)
Bank Ontology
Beta Cell Genomics Application Ontology (BCGO)
BioAssay Ontology
Bioinformatics Web Service Ontology
Biological Collections Ontology (BCO)
Biomedical Ethics Ontology
Biomedical Grid Terminology (BiomedGT, retired)
BioTop: A Biomedical Top-Domain Ontology

Environment Ontology (ENVO)
Epidemiology Ontology (EO)
Epilepsy and Seizure Ontology (EPSO)
Evolution Ontology (EO)
Experimental Factor Ontology (EFO)
EXperimental ACTioins Biomedical Protocol Ontology (EXACT2)
Exposé: An Ontology for Data Mining Experiments
Flybase Drosophila Anatomy Ontology (FBBt)
Fission Yeast Phenotype Ontology (FYPO)
Flower-Visiting Domain Ontology (FV)
Flower-Visiting Behavior Application Ontology (FVB)
Foundational Model of Anatomy (FMA) Ontology
Gastrointestinal Endoscopy Ontology (GIEO)
Gene Regulation Ontology (GRO)
General Information Model (GIM)
Genomic Feature and Variation Ontology (GFVO)
Gestalt: Federated Access to Cyber Observables for Detection of Targeted Attack
Health Data Ontology Trunk (HDOT)
Human Interaction Network Ontology (HINO)
Human Physiology Simulation Ontology (HuPSON)
Infectious Disease Ontology (IDO)
Information Artifact Ontology (IAO)
Informed Consent Ontology (ICO)
Interaction Network Ontology (INO)

http://basic-formal-ontology.org/users

Cancer Cell Ontology (OncoCL)
Cancer Chemoprevention Ontology (CanCo)
Cardiovascular Disease Ontology (CVDO)
Cell Behavior Ontology (CBO)
Cell Cycle Ontology
Cell Expression, Localization, Development and Anatomy Ontology (CFLDA)
# Industrial Ontologies Foundry

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Industrial Ontologies Foundry (IOF) initiative, to create a suite of interoperable high quality ontologies covering the domain of industrial (especially manufacturing) engineering
Industrial Ontologies Foundry – GOVERNMENT

NIST
• Nenad Ivezic
• Boonserm Kulvatunyou
• KC Morris
• Vijay Srinivasan
• Ram Sriram
• Paul Witherell
• Evan Wallace
• ...

Air Force Research Lab
• Clare Paul
Potential collaborating partners

• AFRL / AFMC
  AFRL Air Vehicle Platform Ontology

• Jet Propulsion Lab (+DoD, ...)
  Semantic Technologies for Systems Engineering Working Group (STSEWG)

• European Materials Modeling Council
  • European Materials Modeling Ontology (EMMO)
Industrial Ontologies Foundry – INDUSTRY

- Airbus
- **Autodesk**
- Cambridge Semantics
- CIMData
- CUBRC
- Dassault Industries
- ...


Industrial Ontologies Foundry – ACADEMIA

• Clemson University (Venkat Krovi)
• École polytechnique fédérale de Lausanne (Dimitris Kiritsis)
• INP-ENIT, University of Toulouse (Hedi Karray)
• Loughborough University, UK (Bob Young)
• National Center for Ontological Research (Kemper Lewis, Neil Otte Rahul Rai, Ron Rudnicki, Barry Smith)
• Penn State (Timothy Simpson)
• Texas State (Farhad Ameri)
• UMass Amherst (Ian Grosse)
• University of Toronto (Michael Grüninger)
• ...
Common Core Ontologies for Data Integration

The Common Core Ontology Method

The Data Science and Information Fusion Group’s work in ontologies started in 2008. Since 2010, our participation in IARPA’s Knowledge, Discovery and Dissemination program focused our work on the development of the Common Core Ontologies (CCO).
The Common Core Ontologies
Basic Formal Ontology

The Common Core Ontologies

- Quality
- Time
- Agent
- Artifact
- Event
- Unit
- Geospatial
- Info
Proposed IOF suite of common ontologies to support interoperability of manufacturing software especially for small and medium-sized companies
MatOnto: A suite of ontology modules based on BFO

Existing ontologies in process of being re-engineered to be BFO-conformant:

   for **Laminated Composites**: SLACKS (UMass)
   for **Functionally Graded Materials**: FGMO (NCOR, Milan Polytechnic)

Existing ontologies already BFO-conformant:

   for **Polymers**: CHEBI (EBI)

See: http://ncorwiki.buffalo.edu/index.php/MatOnto_Ontology_Meetings
EMMO

the EUROPEAN MATERIALS MODELLING ONTOLOGY

Emanuele Ghedini (University of Bologna)
Adham Hashibon (Fraunhofer IWM)
Jesper Friis (SINTEF)
Gerhard Goldbeck (Goldbeck Consulting)
Georg Schmitz (ACCESS)
Anne de Baas (European Commission)
BFO: `material_entity`

Diagram:

```
Independent Continuant
  is a
Material Entity
  is a
  Immaterial entity
```
BFO: *object* (& its siblings)
BFO: fiat_object_part
BFO: *object_aggregate*

not a mereological sum of objects, but something like a set:
BFO: `object_aggregate`

not a mereological sum of objects, but something like a set:
BFO: object_aggregate

can change its members over time
examples: collections, populations, families, tribes, species, planetary systems – anything associated with a count, a registry, an inventory, a census
inventory
EMMO RELIES ON THE STRUCTURE OF BASIC FORMAL ONTOLOGY (BFO).

The Basic Formal Ontology (BFO) is a small, upper level ontology that is designed for use in supporting information retrieval, analysis and integration in scientific and other domains. BFO is a genuine upper ontology. Thus it does not contain physical, chemical, biological or other terms which would properly fall within the coverage domains of the special sciences.

The theory behind BFO was developed in 2002 first by Barry Smith and Pierre Grenon.

http://basic-formal-ontology.org/

NOTE: material_entity (BFO) is any independent continuant that has some portion of matter as part (e.g. ‘human being’).

Hence: material_entity (BFO) is not the same as ‘material entity’ in RoMM and not the same as ‘material’ from the chemistry or engineering point of view.
EMMO relies on the structure of Basic Formal Ontology (BFO).

BFO hierarchy:

- 'independent continuant'
- 'material entity'
- 'immaterial entity'
- 'continuant fiat bounda'
- 'spatial region'
- site
- 'continuant fiat bounda'
- 'object'
- 'fiat object'
- 'object aggregate'
- 'process boundary'
- process
- history

BFO is a genuine upper ontology. Thus it does not contain physical, chemical, biological or other terms which would properly fall within the coverage domains of the special sciences.

The theory behind BFO was developed in 2002 first by Barry Smith and Pierre Grenon.

http://basic-formal-ontology.org/
A robust, flexible and multi-perspective ontological framework for representing materials

Since materials are perceived at different scales, the *material entities* (BFO) should be sub-categorized to cover all granularity levels, so that the same material can be represented in EMMO as a black box or as a collection of sub-parts.

*e.g.* a molecule seen as a single rigid body
the same molecule seen as a collection of atoms
EMMO Material Entity Branch Requirements

**OBJECT**

- a causally unified set of *material entities*
- BFO distinguishes thus far 3 varieties of causal unity

**OBJECT AGGREGATE**

- collections having as parts only *objects*
EMMO Mereology Definitions

EMMO basic material entities branch is built upon a hierarchy of mereological relations such as:

- is_part_of
- is_proper_part_of
- is_direct_part_of

By dropping transitivity is_direct_part_of identifies the entity proper parts that are at the very next lower granularity level.

E.g.: nucleus is_direct_part_of atom
     proton is_direct_part_of nucleus

\[ (P_{xy} \land P_{yz}) \rightarrow P_{xz} \]
\[ (P_{xy} \land P_{yx}) \rightarrow x = y \]
\[ PP_{xy} \overset{\text{df}}{=} P_{xy} \land \neg x = y \]

\[ x \equiv x \]
\[ x = y \]
\[ x \subseteq y \]
\[ x \subseteq z \]
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CU 1: *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.

CU 2: *Causal unity via internal physical forces*
Here the material parts of a material entity are combined together causally by sufficiently strong physical 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 neighbourhood.

CU 3: *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.
EMMO Material Entities are defined by a hierarchy of parthood relations, combining the concepts of direct parthood and object.

With EMMO we create a representation of the real world granularity of material entities that follows physics and materials science perspectives.

A ‘material’ in the user case can be described univocally by declaring entities under EMMO hierarchy.

The basic idea is that the ‘material’ can be represented at different levels of granularity, depending on perspective.
RoMM Model Types

RoMM VI

**Electronic Model**
Physics Based Model using a Physics Equation and Material Relation describing the behaviour of electrons quasi particles either as waves, particles or distributions.

**Atomistic Models**
Physics Based Model using a Physics Equation and Material Relation describing the behaviour of atoms either as waves, particles or distributions.

**Mesoscopic Models**
Physics Based Model using a Physics Equation and Material Relation describing the behaviour of Beads either as particles or distributions.

**Continuum Models**
Physics Based Model using a Physics Equation and Material Relation describing the behaviour of Continuum Volume.

One reality with four veridical views each at a different level of granularity.

This is true for observations and for simulations.
EMMO MATERIAL BRANCH (FIRST LEVELS)

ONE REALITY WITH FOUR VERIDICAL VIEWS AT DIFFERENT LEVELS OF GRANULARITY
ONE REALITY WITH FOUR VERIDICAL VIEWS AT DIFFERENT LEVELS OF GRANULARITY.

THE EMMO MATERIAL BRANCH EXTENDS THE BFO MATERIAL ENTITY WITH MATERIAL OBJECTS AT 4 DIFFERENT LEVELS OF GRANULARITY.

- Atom_aggregate
- Meso_aggregate
- Material_object
  - Subatomic_object
  - Atomistic_object
  - Mesoscopic_object
  - Continuum_object
THE EMMO MATERIAL BRANCH EXTENDS THE BFO MATERIAL ENTITY WITH MATERIAL OBJECTS AT 4 DIFFERENT LEVELS OF GRANULARITY.

ONE REALITY WITH FOUR VERIDICAL VIEWS AT DIFFERENT LEVELS OF GRANULARITY

Key to understanding systems is here (?)
EACH ‘material’ can be observed at different levels of granularity and can then be modelled using more then one model type.

ONE USER CASE:
MULTIPLE OBSERVATION GRANULARITY LEVELS
MULTIPLE MODEL GRANULARITY LEVELS
THE EMMO MATERIAL BRANCH PROVIDES AN EXTRA LEVEL OF DETAIL AS REGARDS material objects BY INTRODUCING PHYSICS-BASED OBJECT DEFINITIONS

(e.g. photon, nanostructure, solid)
EXAMPLE OF EMMO REPRESENTATION OF A MATERIAL PROCESSING SYSTEM

PLASMA NANOPARTICLE SYNTHESIS REACTOR

NANO DOME

Nanomaterials via Gas-Phase Synthesis: A Design-Oriented Modelling and Engineering Approach

NANO DOME

Nanomaterials via Gas-Phase Synthesis: A Design-Oriented Modelling and Engineering Approach
EMMO Example on Plasma Nanoparticle Synthesis Reactor

PLASMA REACTOR system

has_direct_part

has_member_part

ICP TORCH system, component

REACTOR VESSEL component, solid_object

COIL component

CONFINEMENT TUBE component

PROBE component

CHAMBER site

PROCESSING GAS EULERIAN fluid_object

Ar ATOM 1 atom_object

Ar ATOM 2 atom_object

Ar ATOM n atom_object

PROCESSING GAS LAGRANGIAN atom_aggregate

Si ATOM 1 atom_object

Si ATOM 2 atom_object

Si ATOM m atom_object

Si MICROPARTICLES LAGRANGIAN object_aggregate

Si MICROPARTICLE 1 solid_object

Si MICROPARTICLE 2 solid_object

... Si MICROPARTICLE r solid_object

Si NANOPARTICLES EULERIAN continuum_object

Si NANOPARTICLE 1 nano_structure

Si NANOPARTICLE 2 nano_structure

... Si NANOPARTICLE p nano_structure

Si NANOPARTICLES LAGRANGIAN meso_aggregate

Si NUCLEUS i nucleus_object

ELECTRON j nucleus_object

Si ATOM 1 atom_object

Si ATOM 2 atom_object

... Si ATOM q atom_object
ONE USE CASE, MULTIPLE MODELS

- the choice of the model to apply for a particular part of the use case is done by the modeller
- more than one approach can be used for the same component
- this approach facilitate a multi-scale approach

One ontology to rule them all.
BFO 2.0

- Very small
- Evolves very slowly
- Strictly formal (= domain neutral) ontology
- Designed to support the consistent representation of different domains of reality in support of scientific research
- Associated with aggressive program of project-based testing, feedback, training, documentation
- Active user forum
- Large user base
BFO backbone taxonomy
BFO: A First Look

Continuant

- Independent Continuant
- Specifically Dependent Continuant

Occurrent (Process, Event)

types

instances
Continuant

Independent Continuant

Non-realizable Dependent Continuant (quality)

Specifically Dependent Continuant

Realizable Dependent Continuant (function, role, disposition)
BFO backbone taxonomy

- Very small
- Evolves very slowly
- Strictly formal (= domain neutral) ontology
- Designed to support the consistent representation of different domains of reality in support of scientific research
- Associated with an aggressive program of project-based testing, feedback, training, documentation
- Active user forum
- Large user base

Diagram:

- Entity
  - Continuant
    - Independent Continuant
    - Generically Dependent Continuant
    - Specifically Dependent Continuant
      - Material Entity
      - Immaterial entity
        - Object
        - Fiat Object Part
        - Object Aggregate
    - Site
  - Occurrent
    - Process
    - Process Boundary
    - Temporal Region
    - Spatiotemporal Region
      - Zero-dimensional Temporal Region
      - One-dimensional Temporal Region
      - Zero-dimensional Spatial Region
      - One-dimensional Spatial Region
      - Two-dimensional Spatial Region
      - Three-dimensional Spatial Region
    - Quality
    - Realizable Entity
      - Process Profile
      - Zero-dimensional Temporal Region
      - One-dimensional Temporal Region
    - Relational Quality
    - Role
    - Disposition
      - Function

all relations here are is_a (type_of)
all relations here are is_a (type_of)
specifically depends on

Continuant

Independent Continuant

Specifically Dependent Continuant

Occurrent

Process
What does ‘specifically_depends_on’ mean?

To say that type A specifically_depends_on type B, is to say that every instance of A requires some instance of B in order to exist

\[ \text{headache depends_on head} \]

All instances of headache depend on some instance of head

This all-some rule applies to all relations other than is_a
Examples of relations

is_a
specifically_depends_on
bearer_of
part_of
has_part
located_in
realizes
has_participant
The All-Some Rule

Before we add a relational assertion

\[ A R B \]

to an ontology graph, we need to check that

all instances of \( A \) stand in the instance-level counterpart of \( R \) to some instance of \( B \)
<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:15 PM</td>
<td><strong>Example Ontology from the SE Domain</strong></td>
</tr>
<tr>
<td></td>
<td>Functions</td>
</tr>
<tr>
<td></td>
<td>Capabilities</td>
</tr>
<tr>
<td></td>
<td><strong>BFO-based Ontology for Information Entities</strong></td>
</tr>
<tr>
<td></td>
<td><strong>AFRL Digital Thread/Digital Twin</strong></td>
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<tr>
<td></td>
<td><strong>Product Life Cycle (PLC) Ontology</strong></td>
</tr>
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<td></td>
<td><strong>Commodities, Services and Infrastructure</strong></td>
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<tr>
<td>3:00 PM</td>
<td>Break</td>
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<tr>
<td>3:15 PM</td>
<td><strong>Interactive session: Defining 'system'</strong></td>
</tr>
<tr>
<td>4:30 PM</td>
<td>Adjourn</td>
</tr>
</tbody>
</table>
[Example Ontology from SE Domain]

- Mission
  - Requirement
    - specifies
    - Function
      - Component
        - performs
        - presents
          - Interface
        - deploys
          - Mission
            - executes
              - Project
                - pursues
                  - Objective
[Example Ontology from SE Domain]

- Requirement
  - specifies
  - Requirement

- Function
  - performs
  - Component

- Component
  - presents
  - Interface

- Interface
  - deploys
  - Mission

- Mission
  - executes
  - Project

- Project
  - pursues
  - Objective

- Objective

- Mass

Example Ontology:
- Mission
- Requirement
- Function
- Component
- Interface
- Mass
is the all-some rule satisfied here?
is the all-some rule satisfied here?
is the all-some rule satisfied here?

No
extra layer needed
extra layer needed
when component fails, its function still exists
quality specifically_depends_on_bearer

- Continuant
  - Independent Continuant
    - thing
  - Specifically Dependent Continuant
    - quality
- Occurrent
  - process, event

quality depends on bearer
complex quality = pattern

Continuant

Independent Continuant
aggregate of things

Specifically Dependent Continuant
pattern

Occurrent
process, event
realizables go hand in hand with processes of realization
realization (when it happens) specifically_depends_on realizable

- Continuant
  - Independent Continuant bearer
  - Realizable Specifically Dependent Continuant
- Occurrent
- Process of realization
Specifically dependent continuants

the *quality* of my hair: to be grey

realizables

your *role* as auditor of this lecture,

my *disposition*: to fidget with my nose, to say ‘erm’

my *capability*: to speak English, to type

*function* of my hands: to grip, to exert pressure, …
Specifically dependent continuants

the *quality* of this phone: to weigh 6.63 oz

the *role* of this room: as lecture hall

the *disposition* of this bulb: to get hot

the *capability* of this room: to have its temperature adjusted

the *function* of that heater: to heat
More examples of specifically dependent continuants

**Quality**: temperature, mass, color, length

**Realizables:**

- **Role**: nurse role, pathogen role, food role
- **Disposition**: fragility, virulence, disease risk factor
- **Capability**: to speak Greek, to swim, to make friends
- **Function**: to pump (of the heart), to unlock (of the key), to transport
<table>
<thead>
<tr>
<th>Continuant</th>
<th>Occurrent</th>
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</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td><strong>Functioning</strong></td>
</tr>
<tr>
<td>to pump</td>
<td>pumping</td>
</tr>
<tr>
<td>to ignite</td>
<td>igniting</td>
</tr>
<tr>
<td>to drain</td>
<td>draining</td>
</tr>
</tbody>
</table>

Some functions (of a fence, to keep people or things in or out; of a heart, to pump) are realized continuously.

Some functions (of a gun, to fire) are realized occasionally.

Some functions (of this sperm, to penetrate an egg) exist without ever being realized.
Examples of realizables

- plan
- function
- role
- disposition
- capability
- tendency

continuants
Their realizations

- execution
- exercise
- realization
- application
- operation
- performance
- functioning

{ occurrences }
An ontology is an agreement on usage, rather than a dictionary.
extra layer needed
[Example Ontology from SE Domain]

- **Function**
  - **Component**
    - **HwComponent**
      - **FlightHwComponent**
        - **mass**
      
    - **Antenna**
    - **Main Engine**
    - **Solar Panel**
      - **Reflector**
      - **Feedhorn**

- **Mission**
  - **Project**
  
- **Human Component**
  - **Person**
  - **Organization**

- **Interface**
  - **Objective**

- **presents**
- **performs**
- **deploys**
- **executes**
- **pursues**
Use of ‘role’

student =def. human being who bears the student role
lawyer =def. human being who bears the lawyer role

Roles very often go hand in hand with dispositions acquired by the bearer of the role as a result of exercising the role
Role (externally-grounded realizable entity)

role = def. a realizable entity

• which exists because the bearer is in some special physical, social, or institutional set of circumstances in which the bearer does not have to be, and

• is not such that, if it ceases to exist, then the physical make-up of the bearer is thereby changed.
Disposition (an internally-grounded realizable entity)

\[ \text{disposition} = \text{def.} \]

a realizable entity which if it ceases to exist, then its bearer is physically changed, and

whose realization occurs when this bearer is in some special physical circumstances, in virtue of the bearer’s physical make-up
Capability (a beneficial disposition)

*Capability* = def.

a disposition whose realization

1. can be graded on a scale starting from zero
2. is such that its realization brings benefits either
    
    to the bearer or a group to which the bearer belongs
    (family, organization, …)
    
    or: to the owner or user of the bearer (where the bearer is an artifact)
A Thesaurus-Guided Framework for Visualization of Unstructured Manufacturing Capability Data

Authors

Farhad Ameri, William Bernstein

Conference paper
First Online: 31 August 2017

Part of the IFIP Advances in Information and Communication Technology book series (IFIP, volume 513)
Function (a disposition designed or selected for)

*Function* = def.

a capability 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 kind.
Artifacts have functions

An artifact’s function is the reason why the artifact was built (why the bearer of the function exists)
Artifacts have functions

An artifact’s function is the reason why the artifact was built (why the bearer of the function exists)

But artifacts also have capabilities (e.g. to operate at high temperature, to operate continuously,
Artifacts have functions and other capabilities

An artifact’s function is the reason why the artifact was built (why the bearer of the function exists)

But artifacts also have capabilities (e.g. to operate at high temperature, to operate continuously, to operate safely, ...)
Capability of an engineered artifact

=def. a disposition of an engineered artifact whose realizations can be graded along a scale in a way that tracks degree of benefit to the owner or user of the artifact
Function of an engineered artifact

=def. capability of an engineered artifact which exists because an entity was needed to function (operate, perform) in just this way
One idea for a schematic definition of ‘engineered system’

• An engineered system $s$ is an aggregate of engineered artifacts $a_1, ..., a_m$
• Each of the artifacts $a_i$ has functions $a_i:f_1, ..., a_i:f_n$ and capabilities $a_i:c_1, ..., a_i:c_p$
• $s$ itself has function $f$, and $s$ exists because something was needed to realize function $f$, and $f$ is realized through the coordinated realization of $a_i:f_1, ..., a_i:f_n$ and $a_i:c_1, ..., a_i:c_p$
[Example Ontology from SE Domain]

- **Function**
  - **Component**
    - **Mission**
      - **Project**
    - **Objective**
      - **Interface**
    - **Human Component**
      - **HwComponent**
        - **FlightHwComponent**
          - **mass**
        - **Person**
        - **Organization**
      - **Objective**
        - **Antenna**
        - **Main Engine**
        - **Solar Panel**
          - **Reflector**
          - **Feedhorn**
Capabilities Engineering
BFO Ontology of Information Entities
BFO Ontology of Information Entities

Types:
- Continuant
  - Independent Continuant
    - Thing
  - Specifically Dependent Continuant
    - Attribute
- Occurrent
  - Process

Instances:
BFO Ontology of Information Entities

- **Continuant**
  - **Independent Continuant**
    - thing
  - **Specifically Dependent Continuant**
    - attribute
  - **Generically Dependent Continuant**
    - information entity

- **Occurrent process**

**Types**

**Instances**
Specifically Dependent Continuants

if the bearer ceases to exist, then its quality, function, role ceases to exist

the color of my skin

the function of my heart to pump blood

my weight
Generically Dependent Continuants

if one bearer ceases to exist, then the entity can survive, because there are other bearers (copyability)

the pdf file on my laptop

the DNA (sequence) in this chromosome
Relation of Concretization

GDC: novel
SDC: pattern of ink marks on the pages of a copy of the novel

GDC: plan specification
SDC: concretization of this plan specification in the patterns of ink in this printed document
SDC: concretization of this plan specification in your head (allowing you to adopt it as the specification of your plan)
experimental protocol

This experimental protocol instance of plan specification.

The protocol is concretized in the mind of the leader of the research team in the form of a plan to carry out the experiment, which is an instance of process.

The process realizing this plan starts with the creation of a series of sub-protocols, which are plan specifications for each team member.

The experiment itself is the sum of the realizations of these plans, having outputs further information entities, such as publications, databases ...
and similarly for the engineering design / testing process

This **engineering design instance of artefact specification**

*Artefact specification is a GDC*

The **design is concretized in** the mind of a prototype builder who converts it into a **plan to build a prototype** for use in processes of testing the design

The **process realizing this plan has output** some **instance of prototype artifact.**
Unlocking Digital Thread Data for More Effective & Economical Systems Health Monitoring

with thanks to Ron Rudnicki, CUBRC
Digital Twin (Glaesgen and Stargel, 2012)

an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.

https://ntrs.nasa.gov/search.jsp?R=20120008178
A Continuum of Authoritative Digital Surrogate Representations Leveraged Over the Entire Life Cycle

Grizelda Loy-Kraft, Transitioning to Decisions-Based Informed Lifecycle Tools

CLEARED for public release by 88ABW-2017-1747
Ontologies vs Databases

- can be relatively stable and can be centrally managed

- databases differ massively from enterprise to enterprise and from one day to the next
Ontological Semantic Concept Alignment and Refinement (OSCAR) – extension of KARMA tool from USC:
http://usc-is-i2.github.io/karma/

transforms into RDF graphs data about products, parts, functional capabilities, failure modes, tests, test equipment and locations, failures, root causes, corrective actions ...
examples of questions to be answered by data in ontological representation (as RDF graphs)

- **(Airforce)** Return the 25 products having the longest durations of unscheduled maintenance during 2016
- **(Manufacturer)** How have changes in the quality of vendor-supplied parts led to product failures over time?
- **(Manufacturer)** How do the parts supplied by different suppliers affect testing outcomes of assembled products?
<table>
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<th>LOT ID</th>
<th>Inflation Device ID</th>
<th>FLU-12 ID</th>
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</tbody>
</table>

Testing data

CLEARED for public release by 88ABW-2017-1747
Inflation device passed an X-ray test during a sample check. The X-ray is performed to ensure there are no cracks or bubbles internal to the body of the device.
Tagging with both type and instance identifiers
Tagging the data according to source organization allows us to query all parts produced by each organization at different times and compare their test results

Organization 1 produces Product 1 using
Product 2 produced by Organization 2 using ...
Question: How do the parts supplied by suppliers affect testing outcomes of assembled products?
Organization 1 produces Product 1 using Product 2 produced by Organization 2. Query all those parts produced by different organizations at different times and compare them to the test results.

Question: How do the parts supplied by suppliers affect testing outcomes of assembled products?
OSCAR creates mappings to translate legacy data to ontological representation.

<table>
<thead>
<tr>
<th>Artifact-ID</th>
<th>Lot ID</th>
<th>Inflation Device ID</th>
<th>FLU-12 ID</th>
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Radiographic Exam Token

Radiographic Exam Result

Act of Radiographic Exam

78012_CGI15E002-002_Inflation_De...

http://www.sema...

78012_CGI15E002-002_Inflation_De...

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ontologies allow reasoning over the data
Recall: application ontology of Delta Battery artillery vehicles

“Horizontal Integration of Warfighter Intelligence Data”
http://ontology.buffalo.edu smith/articles/Horizental-integration.pdf
slicing and dicing with ontological representations

once the data are tagged with ontologies we can slice and dice them along different directions:

- all data about *this part (instance)*
- all data about parts of *this type*
- all data about parts from *this supplier*
- all data about *this supplier*
- all data about *costs* associated with parts of this type from this supplier
Enter an aircraft tail number
Ontoview returns all assertions related to that aircraft
Each activity represented as a hyperlink
Assertions are formed by linking one hyperlink to the next

artifact:Aircraft Tail-# SPAF91415 info:correlates local:SerialNumber_7000000456  
local:SerialNumber_7000000456 ro:participates_in local:Maint_1718388407...  
local:Maint_1718388407... ero:occurs_on local:TimeInterval_2015-12-1706:05...  
local:TimeInterval_2015-12-1706:05 info:designated_by local:MaintDurationMeasure...  
local:MaintDurationMeasure... ero:inheres_in local:MaintDurationHrsToken...  
local:MaintDurationHrsToken... has_integer_value n

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SPARQL Query: Return the 25 engines having the longest durations of unscheduled maintenance during 2016

Start with ‘engines’
Create list of assertions
Filter to those assertions relating to ‘unscheduled maintenance’
Output start and end times of unscheduled maintenance for each engine
Calculate stasis hours between end and start times
Rank order
Output list of engines as ranked
Or output list of types of engines as ranked
Building an Ontology-Based Digital Twin for the Aircraft/Engine Product Life Cycle

Sketch of a PLC ontology framework that remains constant across different types of aircraft, engines, operations, systems, data, software tools ...

Rooted in tested ontology approaches, including Joint Doctrine Ontology

with thanks to Dimitris Kiritsis, Lausanne

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Digital Thread/Digital Twin initiative

Advanced Research and Development of Digital Thread / Digital Twin (DT/DTw) Applications for Next Generation (Gen) and Legacy Aerospace Systems and Engines

Goal: To address the stovepipe problems resulting from the fact that airforce bases import data, models, and information from a huge variety of different sources, all of which use their own local terminologies and data models

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Draft of a set of ontology modules for air force logistics

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All ontologies descend from BFO + CCO
Air Force Core Functions and Fleets

Core functions are subtypes of Organization Capability and together with Acts of Organizational Control are used to classify Fleets.
Core functions are subtypes of Organization Capability and together with Acts of Organizational Control are used to classify Fleets. Air Force Core Functions and Fleets include:

- Agile Combat Support
- Air Superiority
- Building Partnerships
- Command and Control
- Cyberspace Superiority
- Education and Training
- Global Integrated ISR
- Global Precision Attack
- Nuclear Deterrence Operations
- Personnel Recovery
- Rapid Global Mobility
- Space Superiority
- Special Operations

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Top level organization of BFO

**types**

- Continuant
  - Independent Continuant
    - thing
  - Dependent Continuant
    - attribute
- Information Entity
- Occurrent
  - process

**instances**

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Top level organization of BFO

- Independent Continuant
  - material entity
- Dependent Continuant
  - attribute
- Information Entity
- Occurrent
  - process
Top Level organization of BFO

Material Entity → Attribute → Information Entity → Process

BFO:Continuant  BFO:Occurrent
Top Level organization of BFO

- Material Entity
  - Attribute
    - Quality
    - Role
    - Disposition
      - Capability
        - Function
  - Information Entity
    - Process

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Top Level organization of BFO

- **BFO:Continuant**
  - Material Entity
    - Quality
    - Role
    - Disposition
      - Capability
        - Function = what a thing was built to do

- **BFO:Occurrent**
  - Process

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Four major top-level categories in BFO

Material Entity: Aircraft, Tail, Airframe, Engine, Sensor, Machine Tool

Attribute: Airbase, Fuel Supply, System, IVHM System*

Information Entity

Process

*Integrated Vehicle Health Management System

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Four major top-level categories in BFO

BFO:Continuant

Material Entity
- Aircraft
- Tail
- Airframe
- Engine
- Sensor

Attribute
- Crack
- Fault
- Discontinuity

Information Entity

BFO:Occurrent

Process

Machine Tool
- Status
- Productivity
- Quality
- Function
- Capability

Airbase
Fuel Supply
System
IVHM System

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We focus on these three BFO categories
<table>
<thead>
<tr>
<th>Material Entity</th>
<th>Information Entity</th>
<th>Process</th>
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<tbody>
<tr>
<td>Joint Doctrine</td>
<td>Technical Manual</td>
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<td>Production Plan</td>
<td>Maintenance Report</td>
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<td>Part List</td>
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<td>Sensor Data</td>
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</table>

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Material Entity  Information Entity  Process

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BFO: Process

Planned Process

Product Life Cycle (PLC)

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Process

*Design Process*  *Production Plan Generation Process*  *Production Process*  *Maintenance Process*  *Use Process*  *End of Life Process*

**BFO: Process**

**Planned Process**

**Product Life Cycle (PLC)**

*Part of*

*Inter-spersed*

*Follows*

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Follows

BFO: Process

Planned Process

Product Life Cycle (PLC)

Design Process

Production Plan Generation Process

Production Process

Maintenance Process

Part of

Part of

Part of

Part of

Follows

Follows

Part of

Has output

Guided-by

Has output

Production Plan

Product

Information Entity

Material Entity

U.S. AIR FORCE

AFRL
Maintenance Plan Generation Process 

Maintenance Plan

Has output

Guided-by

Maintenance Process

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BFO: Process
Planned Process

Product Life Cycle (PLC)

Design Process
Part of
Follows
Production Plan Generation Process

Production Process
Part of
Follows
Maintenance Process

Part of
Follows
Maintenance Plan Generation Process

Has output
Guided-by
Production Plan

Maintenance Plan
Guided-by
Maintenance Plan

Guided-by
Maintenance Report

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BFO: Process

Planned Process

Product Life Cycle (PLC)

Design Process

Production Plan Generation Process

Production Process

Maintenance Process

Part of

Part of

Part of

Follows

Follows

Follows

Part of

Production Plan

Has output

Guided-by

Has-output

Information Entity

Material Entity

Product
Production Plan

Generation Process

Design

Process

Follows

Possession, Storage

Operations

End of Life Process

Product Life Cycle (PLC)

Maintenance Plan

Generation Process

Follows

Maintenance Process

Part of

Sortie (Plan) Generation Process

Has output

Guides

Part of

Flight

Sortie

Air Mission

Part of

Air Force Planning Doctrine

Air Force Operations Doctrine

Joint Planning Doctrine

Joint Operations Doctrine

Part of

Air Force Planning Doctrine

Frames*

Part of

Joint Operations Doctrine

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Part of

Joint Planning Doctrine

Part of

Sortie Plan

Has output

Guides

Part of

Sortie

Part of

Air Mission

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Joint Operations Doctrine

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Sortie

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Air Mission

Frames*

Part of

Joint Operations Doctrine

Frames*

Part of

Joint Planning Doctrine

Part of

Sortie Plan

Has output

Guides

Part of

Sortie
Product Life Cycle (PLC)

- Production Process
- Possession, Storage
- Operations
- End of Life Process
- Maintenance Process
- Air Mission
- Sortie
- Sortie (Plan) Generation Process
- Flight
- Maintenance Plan
- Sortie Plan
- Flight Manual
- Air Force Planning Doctrine
- Air Force Operations Doctrine
- Joint Planning Doctrine
- Joint Operations Doctrine

Information Entity

Process

Part of
Follows
Part of
Part of
Follows
Follows
Part of
Part of
Has output
Has output
Frames*
Frames*

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Planned Process

Product Life Cycle (PLC)

- Design process
- Production Plan Generation Process
- Production Process
- Maintenance Plan Generation Process
- Use Process
- End of Life Process

Requirements Specification
- Product Model (Drawing, ...)
- Production Plan
- Maintenance Plan
- User Documentation

Information Entity

Material Entity

Portion of Raw Material
Portion of Waste Material
- Aircraft
- Human being (Designer, Manager, Machinist, Maintenance Engineer, Pilot, Crew, ...)
- Factory (Machine, Building, ...), Repair Depot, Base
- Utility Supply System (Energy, Water, Data ...)

BFO: Process

Follows: Has output

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Material Entities, including Systems

- Aircraft
  - Engine
  - Airframe
  - Weapon System
  - Ammunition

- Procurement Staff
- Designer
- Production Engineer...
- Pilot, Crew
- Maintenance Engineer...
- Airbase, Repair Depot
- Disposal Engineer
- Disposal Facility
- Maintenance (IVHM) System
- Supply System (Fuel, ....)
- Utility System (Energy, Water, Data / IT ...)
- Infrastructure (Transport / Delivery System ... )
Commodities, services and infrastructure (systems)

with thanks to Wolfgang Grassl
Basic Dichotomy between Commodities and Services

• Commodities are continuants
  – material things, software
  – deliberately created and such as to survive their act of creation
  – can be stored, bought, sold, rented,

• Services are occurrents

They are processes; but what sorts of processes?
Traditional examples of services

- haircutting
- consulting
- (aircraft) maintenance
- prostitution
- teaching
- transport (taxi)
- rock concert
- restaurant
What do all these have in common?

- haircutting
- consulting
- (aircraft) maintenance
- prostitution
- teaching
- transport (taxi)
- rock concert
- restaurant
A service is a realization of a capability?

- haircutting
- consulting
- (aircraft) maintenance
- prostitution
- teaching
- transport (taxi)
- rock concert
- restaurant
Production and consumption *coincide*

- haircutting
- consulting
- (aircraft) maintenance
- prostitution
- teaching
- transport (taxi)
- rock concert
- restaurant
Production and consumption *coincide*

- haircutting
- consulting
- (aircraft) maintenance
- prostitution
- teaching
- transport (taxi)
- rock concert
- restaurant

This is why services cannot be stored or rented
What are you paying for when you pay your monthly phone bill?

1. The phone itself
2. The process of using the phone
3. The capability of the phone to receive calls even when you’re not using it
4. The telephone network – a system
Two Kinds of Commodities (Manufactured Goods)

1. consumable (bananas)
2. non-consumable
   – physical infrastructure: roads, sewers, fiber-optic cable networks, ...
   – digital infrastructure: internet contents, software on the net, ...

The latter *afford (allow)* services as an ocean affords swimming
Rental “services”

• When you rent an apartment you are buying the apartment, but only month by month.

• (Ultimate ownership remains with the landlord, but apartment rental is still not a matter of services, but a matter of goods.) (Services of cleaning, ... – may of course be included in your payment)

(Services of buying, selling, negotiating ... may also be included)
Genuine services are characterized by the fact that renting is impossible. Services can only be purchased.
Car Rental “Services”

• When you rent a car, you are buying the car, but only for the next 3 days of its life

(Again, some services – of buying, selling, negotiating – will be included in the price)

(And behind these are further bodies of infrastructure – the legal system, the education system ...
A general feature of systems

They tend to be embedded within larger systems

Rental car hydraulic system
A general feature of systems

They tend to be embedded within multiple larger systems
A general feature of systems

They tend to be embedded within multiple larger systems

- Rental car hydraulic system
- Rental car company maintenance system
- Maintenance engineer training and education systems
A general feature of systems

They tend to be embedded within multiple larger systems.
A general feature of systems

They tend to be embedded within multiple larger systems
Is software a service

• When you buy a piece of shrink-wrapped software you sign a license agreement?
• Are things any different if you download the software from the internet?
• Is this *renting software*, if it becomes unusable after 30 days?
Selling systems

- that price of a service is dependent on the environment in which it is delivered
- the price of a commodity is dependent (in part) on the environment in which it is sold
- the ensemble of environmental features within which a purchase is made (environmental features which are relevant to the purchase)
Bundles of services

True services = production and consumption must coincide

Nearly every commodity goes hand in hand with bundles of:

* greeting/welcoming/explaining services
  - for sales (when you buy a car in the showroom)
  - for delivery (the waiter in the restaurant)
  - for teaching (when the university administrator helps you enroll and pick your courses)

* maintenance services (when you take your car back to be fixed)
When we think we are paying for a service we are nearly always paying primarily for infrastructure

- which means paying for something created which lasts through time even when not being consumed.
  - the internet (cables, ...)
  - car rental
  - telephone service
  - transport (the highway system, the subway system)

  etc. etc.
<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
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<tbody>
<tr>
<td>3:00 PM</td>
<td>Break</td>
</tr>
<tr>
<td>3:15 PM</td>
<td><strong>Interactive session: Defining 'system'</strong></td>
</tr>
<tr>
<td>4:30 PM</td>
<td>Adjourn</td>
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Systems
**Environment Ontology**

**Class: urban flooding**

**Term IRI:** [http://purl.obolibrary.org/obo/ENVO_01000718](http://purl.obolibrary.org/obo/ENVO_01000718)

**Definition:** Urban flooding is a flooding process in which land or property in a built environment, particularly in more densely populated areas, is inundated due to the rate of water input exceeding that of water drainage provided by the environment's drainage systems.


**Annotations**

- **editor note:** Relevant to built environments and can be linked to urban flows. Also relevant to water and sanitation SDGs.
- **in_subset:** environmental_hazards

**Class Hierarchy**

- **Thing**
  - **entity**
    - **occurrence**
    - **process**
      - **environmental_system_process**
        - **hydrological_process**
          - **flooding**
            - **coastal_flooding**
            - **riverine_flooding**
            - **flash_flooding**
            - **areal_flooding**
            - **urban_flooding**
BFO: site
A cave (site)

Fiat boundary
Ambiguity of ‘Manhattan’

- Manhattan as material entity (a collection of bricks and rock and other solid matter)
- Manhattan as a complex site (the place where people actually live and move)
- Extended Manhattan = the sum of the above

analogously for cave, mouth, nostril, your car, your lab, your bed (getting into bed …)
Five Basic Niche Types

1: a womb; an egg; a house (better: the interior thereof)
2: a snail’s shell;
3: the niche of a pasturing cow;
4: the niche around a circling buzzard (fiat boundary)
5. your digestive tract, the Mont Blanc tunnel
system
environmental system
ecosystem
biome
microbiome

https://bioportal.bioontology.org/ontologies/ENVO
SDGIO = Sustainable Development Goals Interface Ontology (SDGIO)
ENVO Definition

system

=def. A material entity consisting of multiple components that are causally integrated
Examples: solar system, digestive system, forest ecosystem, subway system

Joint Doctrine Definition

system =def. A functionally, physically, and/or behaviorally related group of regularly interacting or interdependent elements; that group of elements forming a unified whole. (JP 3-0)
ENVO Definition

environmental system

= Def. A system which has the disposition to environ one or more material entities.

$a$ environs $b = \text{Def. } a \text{ includes } b \text{ (partially or wholly) within its site and } a \text{ causally influences } b$

Example: The Union Station lost-and-found system
The system includes, for example, the managers of the repository of found items.
ENVO Definition

system
  environmental system
ecosystem
Def. an environmental system that environs living organisms
  biome
  microbiome
subtypes of ecosystem in ENVO

biome
biosphere
ecological corridor
habitat
mouth environment
skin environment
subtypes of ecosystem in ENVO

ecological corridor = Def. An ecosystem which bridges two or more adjoining ecosystems and through which organisms may move or propagate

habitat = Def. an ecosystem which can sustain and allow the growth of a population of organisms of a single species

biome
biome
= def. an ecosystem that is determined by an ecological community

determined by = def. A system is determined by an entity if the removal of that entity would cause the collapse of that system

(e.g. removing the corals from a coral reef ecosystem would cause that ecosystem to collapse)

Systems typically break if you take out their biggest parts.
community = Def. a collection of organisms connected by social or biological relations (biotic interactions).

ecological community = Def. a community of at least two different species living in a particular area.
"at least two different species" may be too narrow. It is possibly that one species but more than one strain. Also, do we consider two or more bacteria or humans (in one species) that form an ecological community?

Yongqun He, 11/10/2017
ENVO-based microbiome definition

system
  environmental system
  ecosystem
  biome
  microbiome

Def. a biome determined by an ecological community of microbiota
biome is a system – includes both environment and inhabitants
1  I agree with your proposed short form, but I don't see what you objection is to the Def. as stated
Barry Smith, 11/4/2017

2  It's like saying "...determined by an ecological community of a microbial community" where it would be better
to say "...determined by a an ecological community composed of microbes" or simply "...determined by a
microbial community"

I added "microbial community" to PCO some weeks ago. Perhaps we can add "microbiota" as a synonym, as I
think these are equivalent.
Pier Luigi Buttigieg, 11/4/2017

1  This doesn't sit well.
Microbiota constitute an ecological community. Perhaps rephrase to:

A biome which is determined by microbiota.

Where microbiota is a subclass of PCO ecological community (that can be added as a note under the "biome is
a system" note)
Pier Luigi Buttigieg, 11/5/2017

2  I am happy with the shorter definition and with the use of as 'microbiota as synonym of 'microbial
community'.Please adjust the slides to fit, so that we can remove these comments
Barry Smith, 11/5/2017
examples of systems

Natural
• solar system
• forest ecosystem
• digestive system

Engineered
• subway system

Even a subway system is embedded in natural systems and has a variety of natural systems embedded within it
Dormant and activated Systems

• Trauma system is activated when message received that a patient is on the way

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5312685/
Human Gastrointestinal Bacteria

Stomach $0 - 10^2$
- Lactobacillus
- Candida
- Streptococcus
- Helicobacter pylori
- Peptostreptococcus

Duodenum $10^2$
- Streptococcus
- Lactobacillus

Distal Ileum $10^7 - 10^8$
- Clostridium
- Bacteroides sp
- Coliforms

Jejunum $10^2$
- Streptococcus
- Lactobacillus

Colon $10^{11}$
- Bacteroides
- Bifidobacterium
- Clostridium coccoides
- Clostridium leptum/Fusobacterium

Proximal Ileum $10^3$
- Streptococcus
- Lactobacillus
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The Environment Ontology

- Material entity
  - Independent continuant
  - Immaterial entity
  - System
  - Object aggregate
  - Flat object part
  - Object
  - Astronomical object
  - Site
  - Environmental zone
  - Ecological community
  - Collection of organisms
  - Ecosystem
  - Population
  - Biome
  - Microbiome
  - Planet
  - Biosphere
  - Ecozone
  - Vegetated area

'is a' relations
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    - Microbiome
  - Biosphere
  - Astronomical body part
    - Astronomical object
      - Astronomical body
        - Planet
- Site
  - Environmental zone
    - Ecorzone
    - Vegetated area
Incorporating microbiome

BFO
ENVO
PCO

‘is a’ relations
Features of systems

Like patterns, systems have fiat boundaries
Are often parts of a larger systems
Often have smaller systems as parts
‘Self-organizing’ systems have something like homeostasis and repair mechanisms to restore homeostasis
An army is a system; the different units within the army influence each other positively
When two opposing armies fight, then they too form a system joined now by negative influence.
Systems Engineering, Definitions (ISO)

(1) Interdisciplinary approach governing the total technical and managerial effort required to transform a set of customer needs, expectations, and constraints into a solution and to support that solution throughout its life. (ISO/IEC/IEEE 2010)
Systems Engineering, Definitions (INCOSE)

(2) An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem:

Operations          Cost & Schedule
Performance         Training & Support
Test                Disposal
Manufacturing

Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (INCOSE 2012)
Systems Engineering, Definitions (SEBoK)

(revises to emphasize the inevitable on-going intertwining of system requirements definition and system design)

• Systems Engineering (SE) is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal.