Ontological Definition of Seamless Digital Engineering Based on ISO/IEC 25000-Series SQuaRE Product Quality Model

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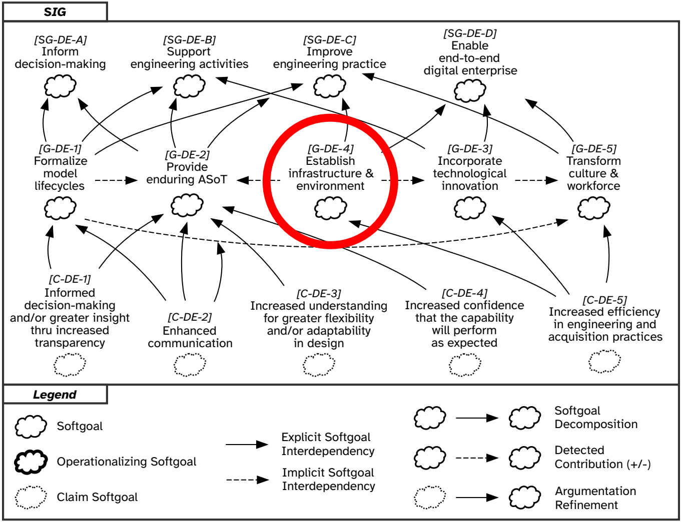
Outline

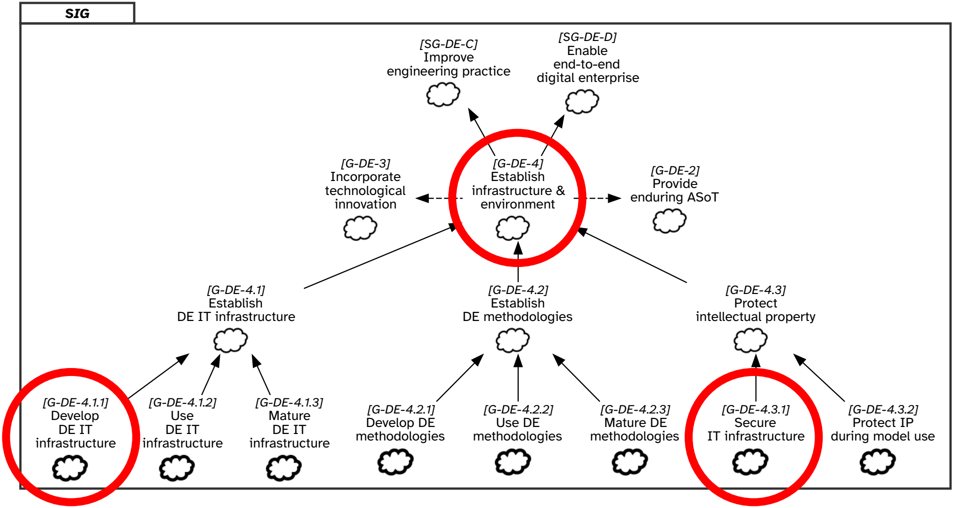
1

Introduction

Digital Engineering Goals: Analyzed and Decomposed



Digital Engineering Goals: Establish Infrastructure & Environment



Challenge: The Normalization of Deviance in Modern Computing

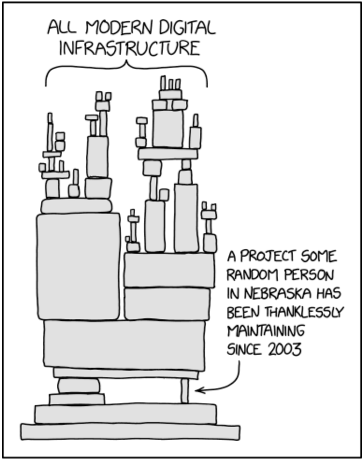
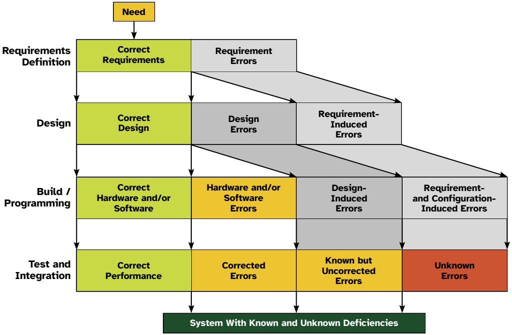


Figure (left): xkcd: Dependency (2020)

Figure (right): The Error Avalanche (2005)

> We build our computer systems the way we build our cities: over time, without a plan, on top of ruins.

Ellen Ullman, *Life in Code: A Personal History of Technology* (2017)



Defining Seamless Digital Engineering

Following prior work in ‘seamless model-driven systems engineering’[1], and inspired by DARPA CRASH[2], CRAFT[3], and META-II[4], we identified and defined a grand challenge[5] in digital engineering research[6]:

Definition (Seamless Digital Engineering)

A digital engineering tooling paradigm that guarantees model coherence and integrity by affording an elegant human-computer interface for systems modeling that is end-to-end formally verified down through the computer hardware.

[1] Broy 2009; Broy et al. 2010; Broy 2020 [2] DARPA 2010a [3] DARPA 2015 [4] DARPA 2010b [5] Moore 2003; Hoare 2003 [6] Wheaton and Herber 2024

Research Contributions

- Ontological definitions of essential concepts in Seamless Digital Engineering, based on the SQuaRE product quality model[1]
- Ontological harmonization of concepts in the systems engineering domain of international standards
- Seamless Digital Engineering Ontology in open-source, machine-readable, standards-based format[2]

https://github.com/systems-praxis/seamless-digital-engineering-ontology

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2

Background

Ontology Development using Protégé and OWL 2

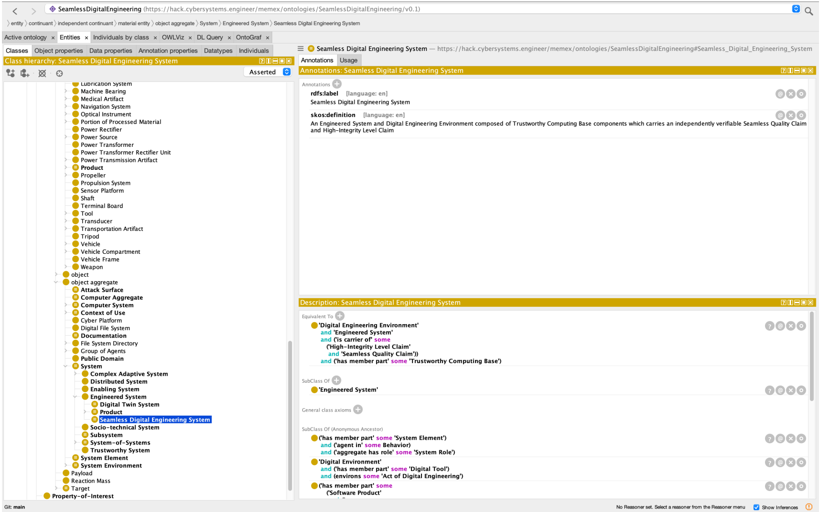
Protégé *is a free, open-source software that allows you to create and manage ontologies for various domains and applications. It supports Semantic Web standards, plug-ins, and web-based access to your knowledge.*

https://protege.stanford.edu/

*The **OWL 2 Web Ontology Language**, informally OWL 2, is an ontology language for the Semantic Web with formally defined meaning. OWL 2 ontologies provide classes, properties, individuals, and data values and are stored as Semantic Web documents.*

https://www.w3.org/TR/owl2-overview/

Ontology Development using Protégé



Logic in Formal Ontology Modeling

OWL Description Logic (DL)[1] is a subset of First-Order Logic (FOL) with extensions:

Symbol	Description
$\mathcal{AL}$	(Attributive Language) Inclusion, equivalence, intersection, and complex definition of classes
$\mathcal{ALC}$	(with Complement) Adds to $\mathcal{AL}$ the empty, complement, union classes [2]
$\mathcal{S}$	Adds the transitivity of relations to $\mathcal{ALC}$
$\mathcal{H}$	Inclusion and equivalence between relations
$\mathcal{O}$	(One of) Classes created with list of all and only the individuals contained
$\mathcal{I}$	(Reverse) Inverse property
$\mathcal{N}$	(Number) Cardinality restriction
$\mathcal{D}_n$	(Countable domain) Definition of domains (data types)

[1] World Wide Web Consortium 2012; ISO 2021a [2] Baader, Horrocks, and Sattler 2008

→ Basic Formal Ontology (BFO)

Basic Formal Ontology[1,2] (BFO-2020 – ISO/IEC 21838-2) contains classes and relations representing content common to all areas of scientific investigation, e.g. object, process, etc. and is used as a top-level architecture by numerous ontologies in the Industrial Ontologies Foundry (IOF), and the **Common Core Ontologies** suite.

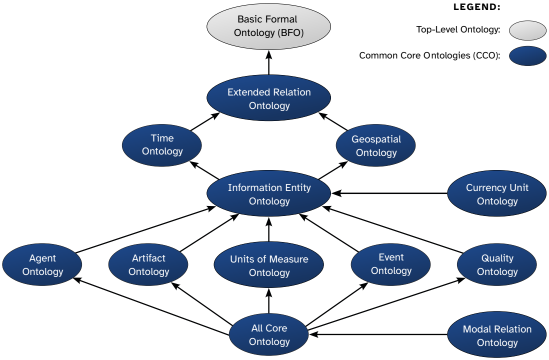
Ontologies conformant to BFO promote *interoperability*, *standardization*, and *reuse* among domain-level ontologies.

[1] Otte, Beverley, and Ruttenberg 2022 [2] https://github.com/BFO-ontology/BFO-2020

→ Common Core Ontologies (CCO)

The **Common Core Ontologies**[1,2] comprise twelve (12) ontologies that are designed to represent and integrate taxonomies of generic classes and relations across all domains of interest.

CCO is a mid-level extension of Basic Formal Ontology (BFO), an upper-level ontology framework widely used to structure and integrate ontologies.



[1] Jensen et al. 2024 [2] https://github.com/CommonCoreOntology/CommonCoreOntologies

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Methodology

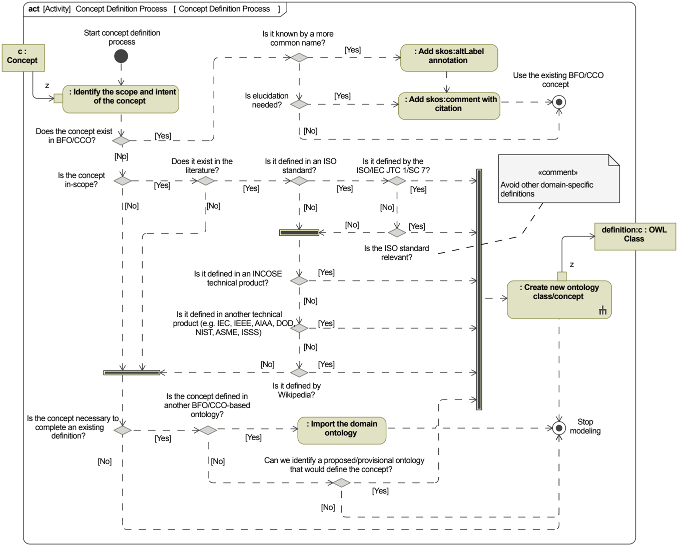
Basic Methodology for Ontology Development

Following Noy and McGuinness[1], we adapted their methodology for OWL 2:

1. Determine the domain and scope of the ontology
2. Consider reusing existing ontologies
3. Enumerate important terms in the ontology
4. Define the classes and the class hierarchy
5. Define the object properties
6. Define the domains/ranges of object properties
7. Create instances (individuals) of classes

[1] Noy and McGuinness 2001

→ Ontology concept definition process using standard sources



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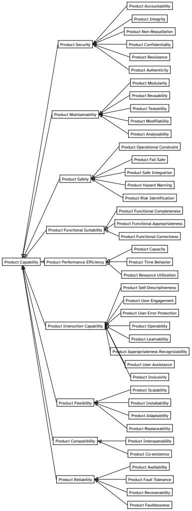
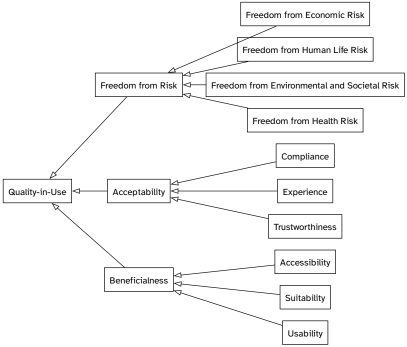
Ontological Definition of Seamless Digital Engineering

➞ ISO/IEC 25000-series SQuaRE Product Quality Model



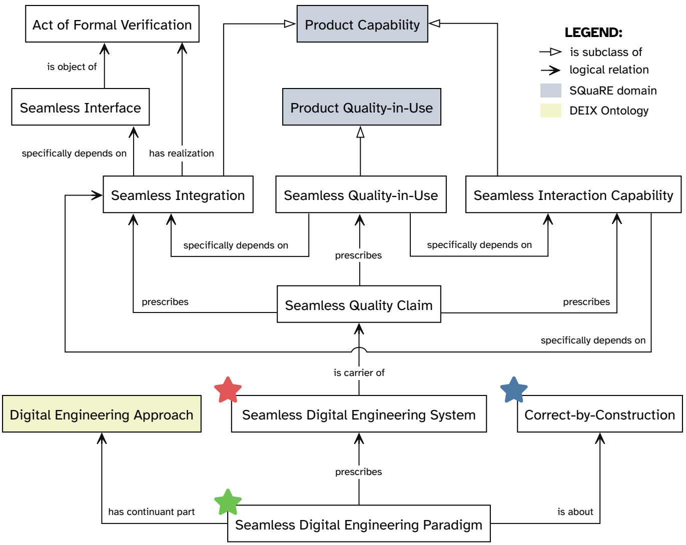


→ The Seamless Digital Engineering Ontology Is Standards-Based

Standard top-level (BFO) and mid-level (CCO) ontologies are the foundation of coherent ontological modeling in the DE domains of knowledge. Relevant international standards include (Table 2):

- **ISO/IEC/IEEE 15288** — System life cycle processes
- **ISO/IEC 25000-series** — Systems and software Quality Requirements and Evaluation (SQuaRE)
- **ISO/IEC/IEEE 15026** — Systems and software assurance
- **ISO/IEC/IEEE 42000-series** — Architecture description and processes
- **ISO/IEC 15408** — (“Common Criteria”) Evaluation criteria for IT security
- **ISO/IEC/IEEE 24641** — Methods and tools for MBSSE

→ Definitions-by-Relations of Concepts in Seamless Digital Engineering



Seamless Digital Engineering Paradigm

Listing 1: **'Seamless Digital Engineering Paradigm'** is a subclass of **Paradigm** equivalent to:

```
    Paradigm
and ('has continuant part' some 'Digital Engineering Approach')
and ('is about' some Correct-by-Construction)
and (prescribes some 'Seamless Digital Engineering System')
```

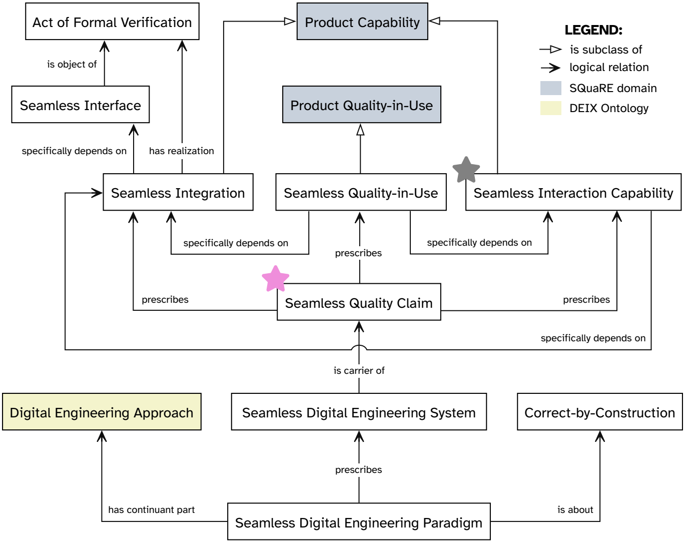
Listing 2: **'Seamless Digital Engineering System'** is a subclass of **'Engineered System'** equivalent to:

```
    'Digital Engineering System'
and 'Engineered System'
and ('is carrier of' some ('High-Integrity Level Claim' and 'Seamless Quality Claim'))
and ('has member part' some 'Trustworthy Computing Base')
```

Listing 3: **Correct-by-Construction** is a subclass of **'Assurance Goal'** equivalent to:

```
    'Assurance Goal'
and ('is concretized by' some 'Integration Process')
and ('is concretized by' some 'Loss of Error')
and (prescribes some 'High-Integrity Level')
and (prescribes some 'Process Outcome')
```

→ Definitions-by-Relations of Concepts in Seamless Digital Engineering



Seamless Quality Claim and Seamless Interaction Capability

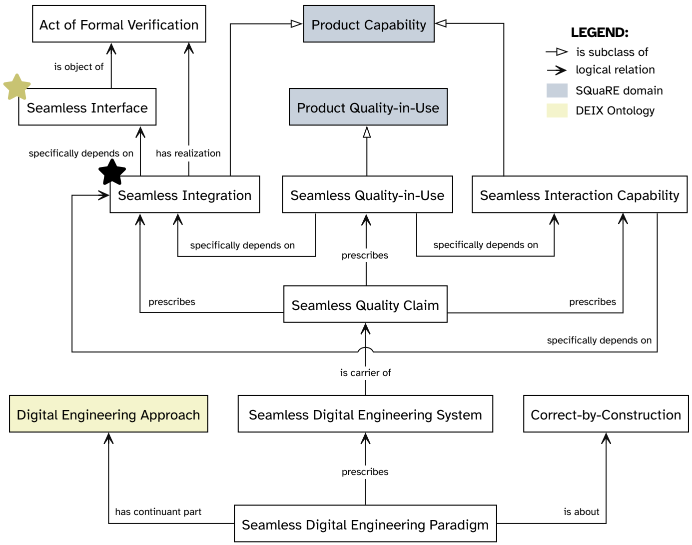
Listing 4: **'Seamless Quality Claim'** is a subclass of **'Quality Claim'** equivalent to:

```
    'Quality Claim'
and (prescribes some 'Seamless Integration')
and (prescribes some 'Seamless Interaction Capability')
and (prescribes some 'Seamless Quality-in-Use')
```

Listing 5: **'Seamless Interaction Capability'** is a subclass of **'Product Capability'** equivalent to:

```
    'Product Interaction Capability'
and ('has continuant part' some
        ('Product Compatibility'
     and 'Product Functional Appropriateness'
     and 'Product Functional Completeness'))
and ('specifically depends on' some 'Seamless Integration')
```

Definitions-by-Relations of Concepts in Seamless Digital Engineering



LEGEND:
- is subclass of
- logical relation
- SQuaRE domain
- DEIX Ontology

Seamless Integration and Seamless Interface

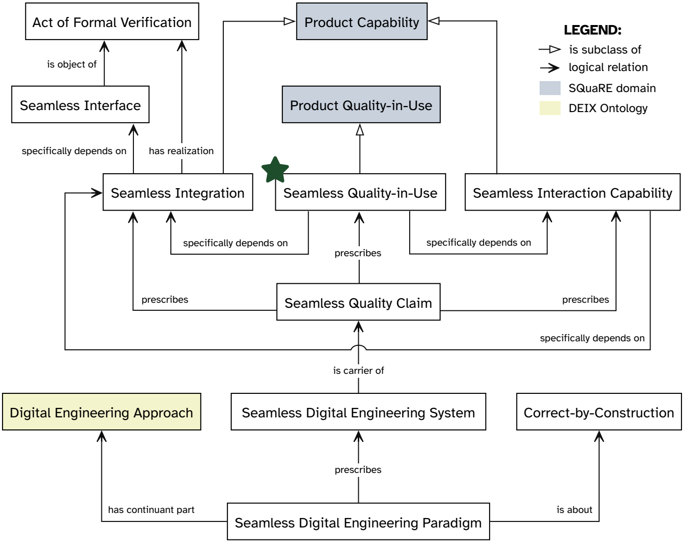
Listing 6: **'Seamless Integration'** is a subclass of **'Product Capability'** equivalent to:

```
    'Product Capability'
and ('has realization' some 'Act of Formal Verification')
and ('has continuant part' some
        ('Product Analysability'
     and 'Product Faultlessness'
     and 'Product Functional Correctness'
     and 'Product Integrity'
     and 'Product Safe Integration'))
and ('specifically depends on' some 'Seamless Interface')
```

Listing 7: **'Seamless Interface'** is a subclass of **'Interface'**, a subclass of 'Information Bearing Artifact', and is equivalent to:

```
    Interface
and ('has continuant part' some 'Proof Certificate')
and ('prescribed by' some 'System Architecture Model')
and ('is object of' some 'Act of Formal Verification')
```

➞ Definitions-by-Relations of Concepts in Seamless Digital Engineering



Seamless Quality-in-Use and Trustworthiness

Listing 8: **'Seamless Quality-in-Use'** is a subclass of **'Quality-in-Use'** equivalent to:

```
    Quality-in-Use
and ('has continuant part' some
         (Experience
     and Suitability
     and Trustworthiness
     and Usability))
and ('specifically depends on' some
         ('Seamless Integration'
     and 'Seamless Interaction Capability'))
```

Listing 9: **Trustworthiness** is a subclass of **'Acceptability'**, a subclass of **'Product Quality-in-Use'**, equivalent to:

```
    Acceptability
and ('specifically depends on' some
         ('Complete Assurance Case Report'
    and ('is carrier of' some 'Trustworthiness Quality Claim')))
```

5

Conclusions and Future Work

Summary

- Concepts from international standards were defined ontologically and harmonized within the BFO and CCO framework
- The natural-language definition of 'Seamless Digital Engineering'[1] was defined ontologically, by relation to harmonized standards-based concepts in systems engineering
  - 'Seamless Integration' is a 'Product Capability' dependent on 'Seamless Interface'
  - 'Seamless Interaction Capability' is a 'Product Capability' dependent on 'Seamless Integration' and other SQuaRE quality characteristics
  - 'Seamless Quality-in-Use' is a quality-in-use super characteristic which depends on 'Seamless Integration' and 'Seamless Interaction Capability'
  - 'Seamless Quality Claim' is a Claim that prescribes these three quality characteristics
- 'Trustworthiness' SQuaRE Quality-in-Use characteristic was defined ontologically based on assurance case and claim concepts defined by ISO/IEC/IEEE 15026[2]
- Seamless Digital Engineering Ontology[3] includes over 500 concepts and 150 axioms, is machine-readable, standards-based, and open-source

[1] Wheaton and Herber 2024 [2] ISO 2019b; ISO 2022c; ISO 2021b [3] Wheaton 2025b

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Future Work

- Completion of ontological definitions of SQuaRE product quality and quality-in-use characteristics
- Continued ontology development of concepts in systems engineering and digital engineering
- Modularization of ontologies as in the proposed import hierarchy shown in Figure 2
- Eventually, model-based and ontology-based international standards in systems engineering and digital engineering

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➞ Questions?

🔗 https://github.com/systems-praxis/seamless-digital-engineering-ontology

Questions? Comments?

Shoutout to Joe Gregory and the INCOSE DEIX WG!

🔗 https://github.com/INCOSE/DEIX_Ontology

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