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Manufacturing Commonsense knowledge : an Enabler for Semantic Explainable AI for trusted flexible Manufacturing

Hedi KARRAY

Scope – CHAIKMAT project

CHAIKMAT4.0
TRUSTED AI-DRIVEN FLEXIBLE MANUFACTURING

- ACRONYM: **CHAIKMAT**
- Project Title: **Commonsense Knowledge & Hybrid Artificial Intelligence for Trusted Flexible MAnufacturing 4.0**
- Coordinator : **Hedi KARRAY**
- Project start date : **10/2021**
- Duration : **48 mois**
- Full cost : **441k€**
- ANR funding : 316k€
- Specific instrument: **Mini Production Line**
- Partners

LGP LABORATOIRE GÉNIE DE PRODUCTION National Engineering School of Tarbes (ENIT)	disp Laboratoire Décision et Information Pour les Systèmes de Production National Institute of Applied Sciences of Lyon (INSA Lyon)
INFONEER Engineering Informatics Research Group Texas State University (TXST)	Center on Knowledge Graphs Information Sciences Institute USC University of Southern California University of Southern California (USC)
GRAIL GEOMETRIC REASONING AND ARTIFICIAL INTELLIGENCE LAB Clemson University	

https://chaikmat-anr.uttop.fr

ONTO COMMONS ONTOLOGY-DRIVEN DATA DOCUMENTATION FOR INDUSTRY COMMONS

Horizon 2020 European Union Funding for Research & Innovation

IOF The Industrial Ontologies Foundry (IOF)

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anr

Industrial Perspective

Why explainability in AI is important ?

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AI adoption

- In 2023, 6% of French companies reported having adopted at least one type of AI technology. That's half as many as in Germany!

- France is below the EU average in terms of AI adoption by businesses.

- Within ten years, AI could add an additional 220 to 240 billion euros to the French GDP."

- Trust and acceptance of AI depend on the specific use case and scope of Prediction or Decision.

Problematic – Need for AI

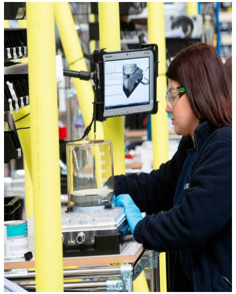
In times like these can a company's manager know whether the production lines are flexible enough to counter such transitions?



Can a Product A be produced under some B constraint?
These questions hold immense importance and need answers...

General Context – Need for Flexibility

Ford switched some of its idled assembly lines from car components to breathing machines to medical supplies, including face masks and reusable gowns.



In 2020, the Hong Kong Innovation and Technology Bureau allocated $800 million to subsidize the production of reusable masks.

What went wrong?

Due to unwanted and uncertain situations, production lines switch from creating undergarments to creating masks. Production lines were not flexible to switch to new customer requirements and it went wrong!

> *“Some people do not like the fabric used for the outer layer. Indeed when I unpacked mine I thought it looked like half a bra. It does not look like a bra, according to my wife, it looks like knickers.”*
>
> **TIM HAMLETT**
> PROF OF history , Journalism & Writer for Hong Kong Free Press

Flexible Manufacturing

Flexibility in manufacturing means the ability to deal with slightly or greatly mixed parts, to allow variation in parts assembly and variations in process sequence or change the production volume and change the design of certain product being manufactured.

1. Routing Flexibility covers the system's ability to be changed to produce new product types, and ability to change the order of operations executed on a part.

2. Machine Flexibility consists of the ability to use multiple machines to perform the same operation, and to absorb large-scale changes, such as in volume, capacity, or capability.

CHAIKMAT Objective

Human-centric Artificial Intelligence (AI) approach that:

- Investigates whether an available set of machines can perform a specific production process (if reconfiguration is needed or some new resource is required)

- Provides human experts with meaningful explanations of how the decision process is conducted.

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Critical Factors Towards adoptiong AI for Flexible Manufacturing

Uncertain or low expectations for return on AI investments
(Trust & Risk)

Personal Judgement overrides AI-based decision-making
(Human Reasoning)

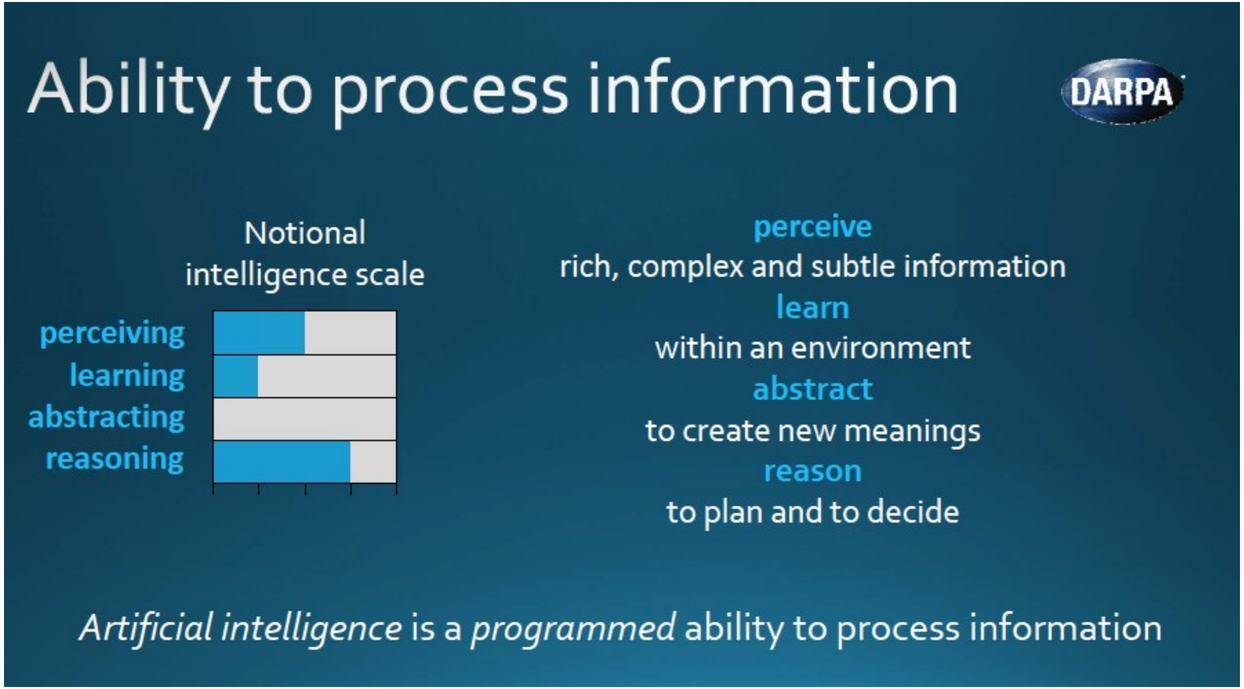
Lack of changes to front-line process after AI adoption
(Agility)

=> Explainable AI

Explainable AI (XAI)

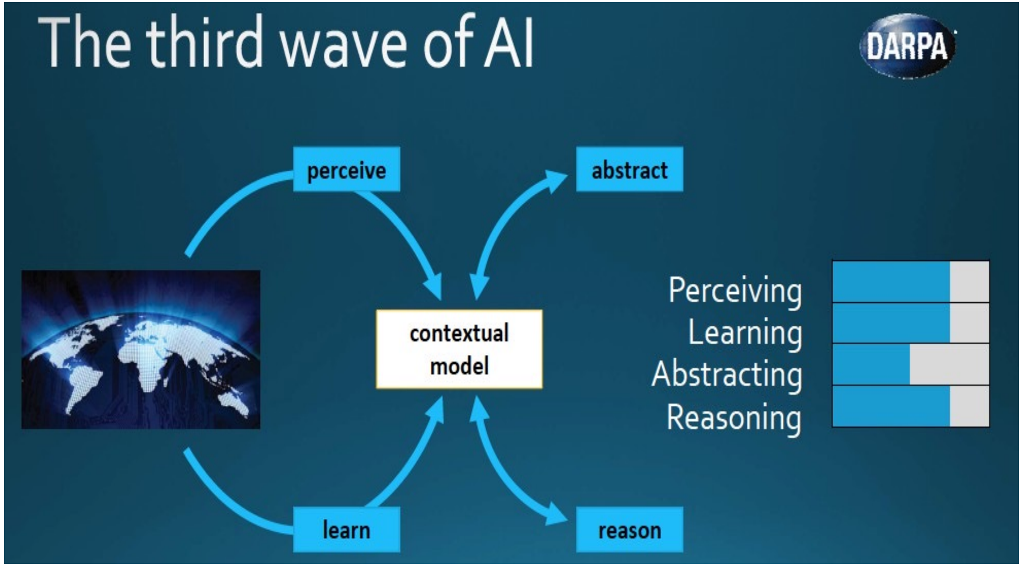
Symbolic, Connexionist, NeuroSymbolic

According to DARPA



(US - Defence Advanced Research Projects Agency)

Explainable AI



XAI focuses on explaining the results generated by AI systems to make them more understandable and to know how the results are obtained

XAI aims to provide explanations to make AI results more understandable and trustable by the users.

The fundamental principle of XAI is to make AI applications fully traceable and make sure that the most influenced factors in regard to results of AI clearly are identified.

XAI has demonstrated impressive practical success specifically in manufacturing (intelligent maintenance, product quality, new product development, and real-time optimization of process parameters).

https://www.darpa.mil/attachments/XAIIndustryDay_Final.pptx

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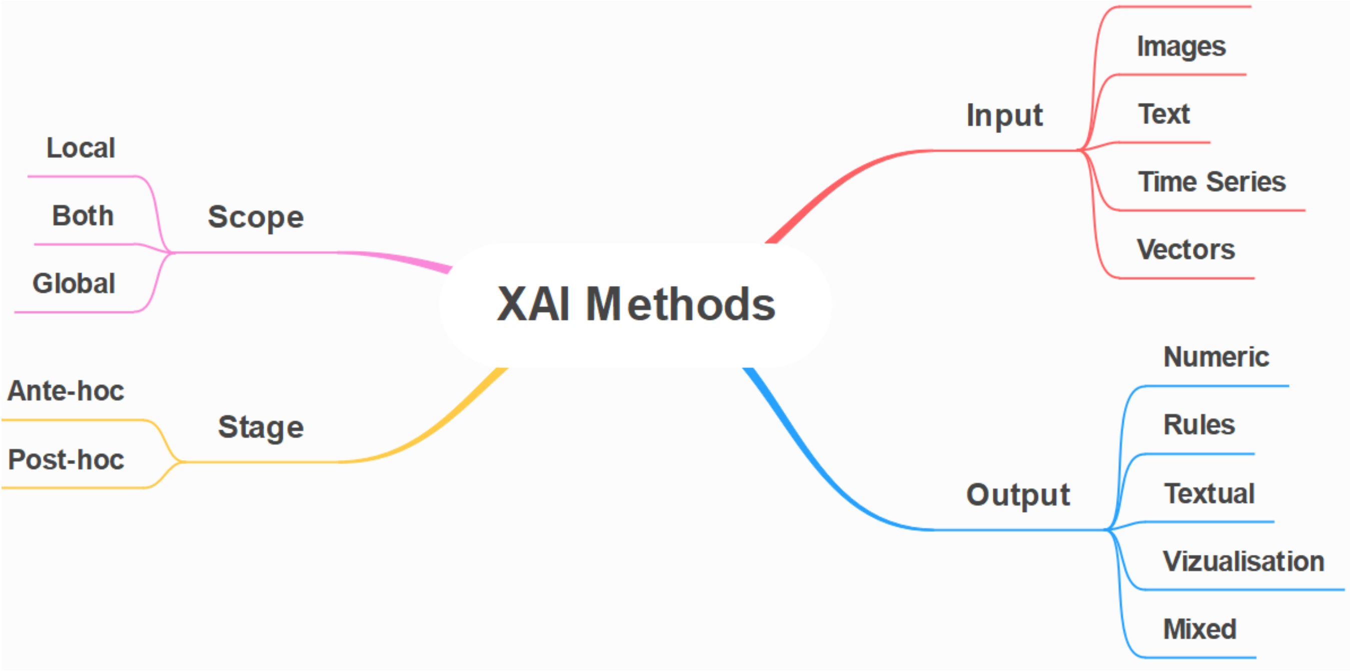
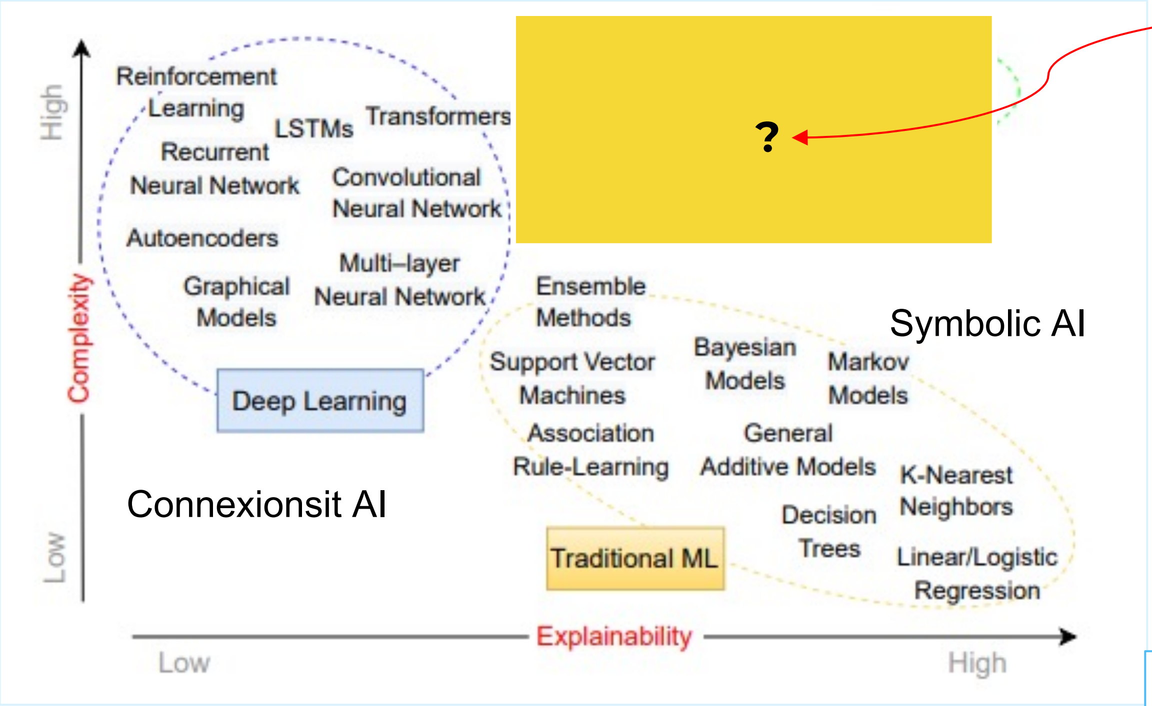
Explainable AI: Methods

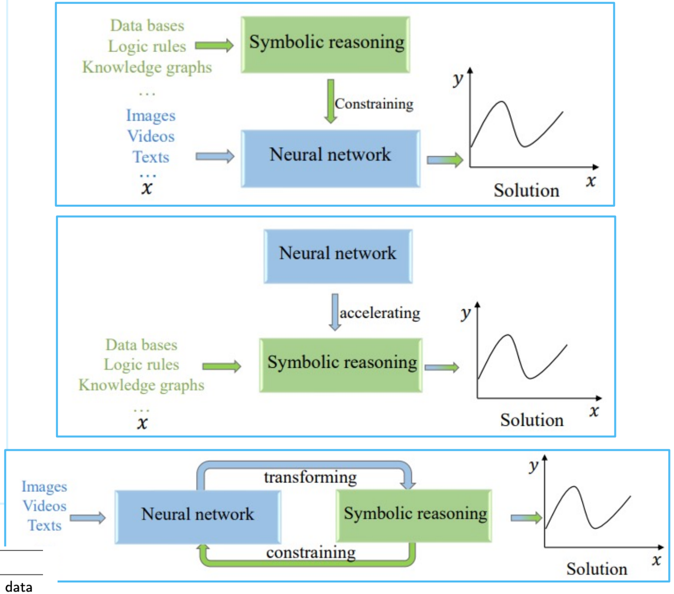


Models complexity Vs Explainability



Knowledge !!

=> Neurosymbolic AI



Clement et al ,2023

Yu et al 2023

Systems	Processing Methods	Knowledge representation	Primary algorithms	Advantages	Disadvantages
Symbolic systems	Deductive reasoning	Logical representation	Logical deduction	Strong generalization ability Good interpretability Knowledge-driven	Weak at handling unstructured data Weak robustness Slow reasoning
Neural systems (Sub-symbolic systems)	Inductive learning	Distributed representation	BP algorithms	Strong at handling unstructured data Strong robustness Fast learning	Weak generalizability (adaptability) Lack of interpretability Data-driven

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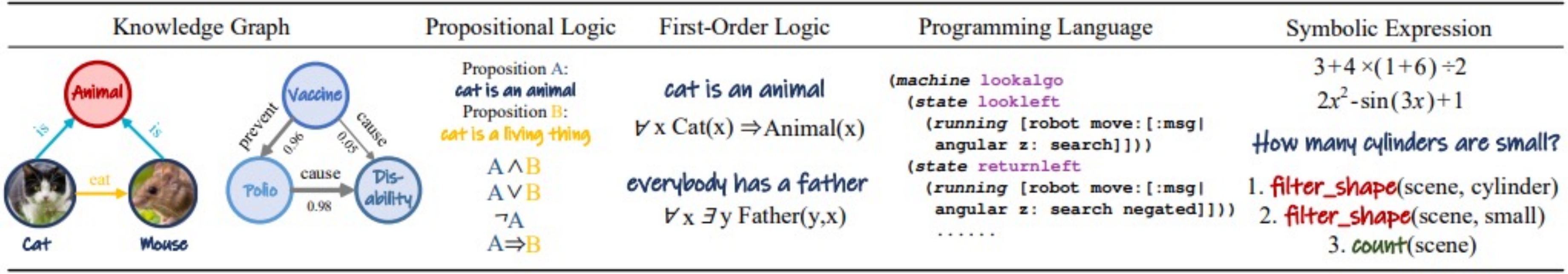
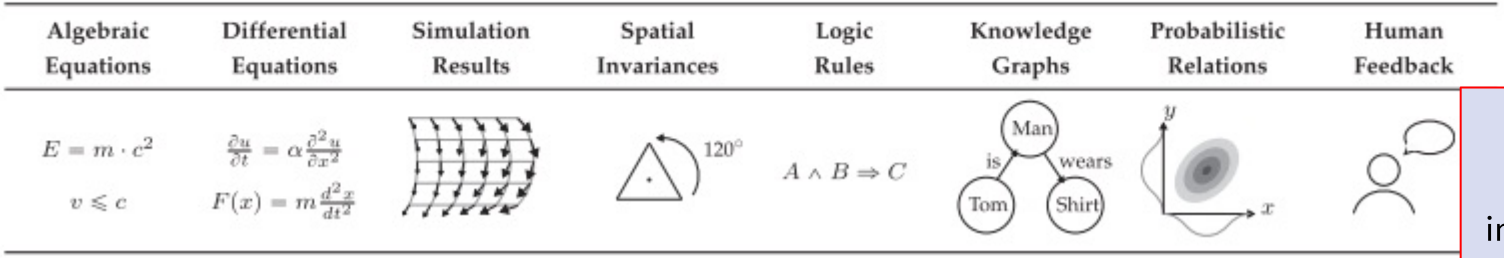
Knowledge Representation



W. Wang, Y. Yang, and F. Wu, 'Towards Data-and Knowledge-Driven Artificial Intelligence: A Survey on Neuro-Symbolic Computing'. arXiv, Oct. 12, 2023 [Online]. Available: http://arxiv.org/abs/2210.15889



Refers to technologies that transform knowledge via direct interfaces between users and machines.

L. Von Rueden *et al.*, 'Informed Machine Learning - A Taxonomy and Survey of Integrating Prior Knowledge into Learning Systems', *IEEE Trans. Knowl. Data Eng.*, pp. 1–1, 2021, doi: 10.1109/TKDE.2021.3079836.

Enablers for explainability

Ontologies and Commons Sense Knowledge

Is Ontology still a thing?

"Allegory of cave" - Plato

Ontology as a branch of philosophy is the science of what is, of the kinds and structures of the objects, properties and relations in every area of reality.

- Ontology is not a data model but a model for relating data to the "Reality".
- Ontology helps us in having a shared view of the "Reality", based on:
  - Consensus
  - Common sense
  - Metaphysics

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Horizon 2020 European Union Funding for Research & Innovation

IOF The Industrial Ontologies Foundry (IOF)

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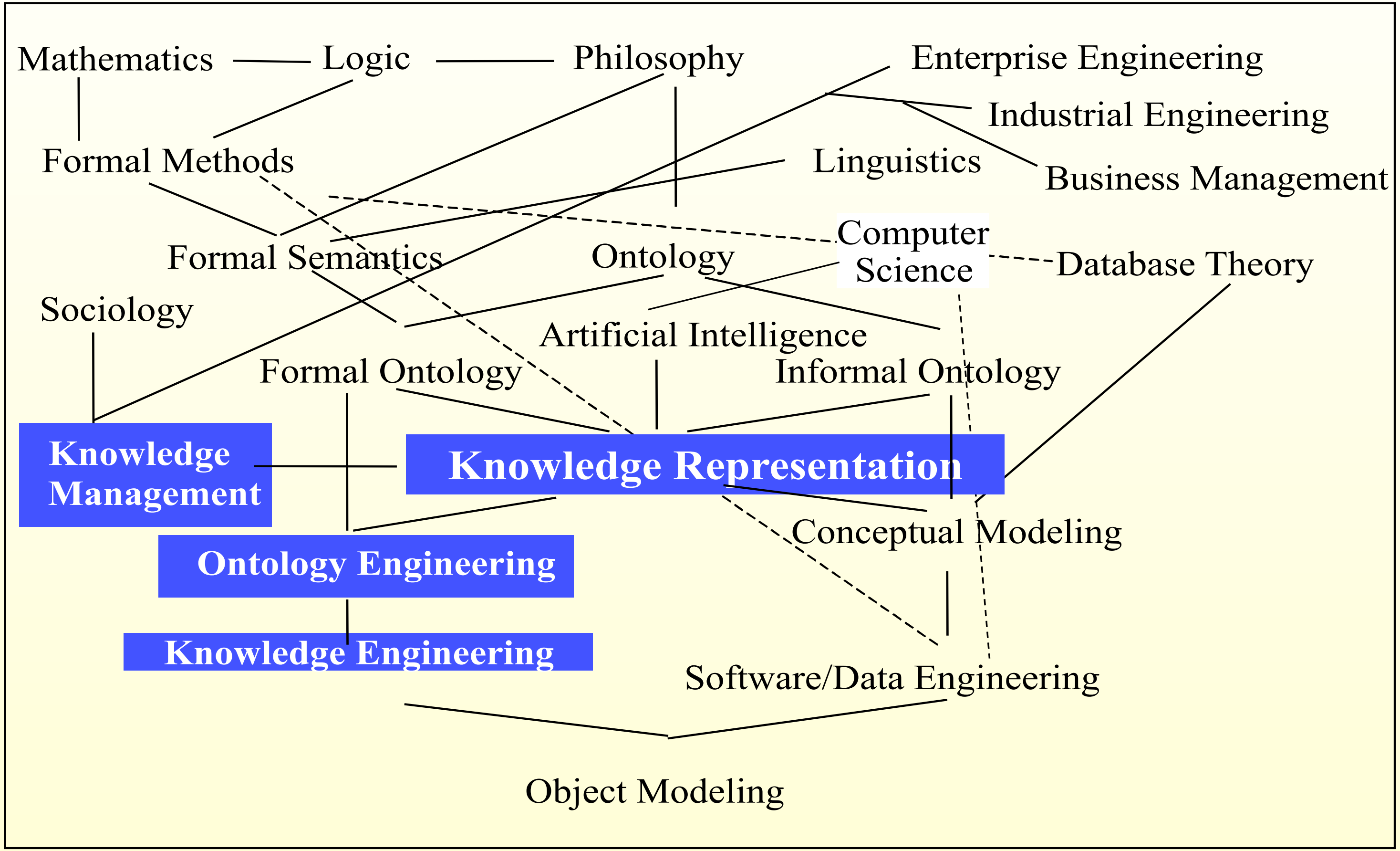
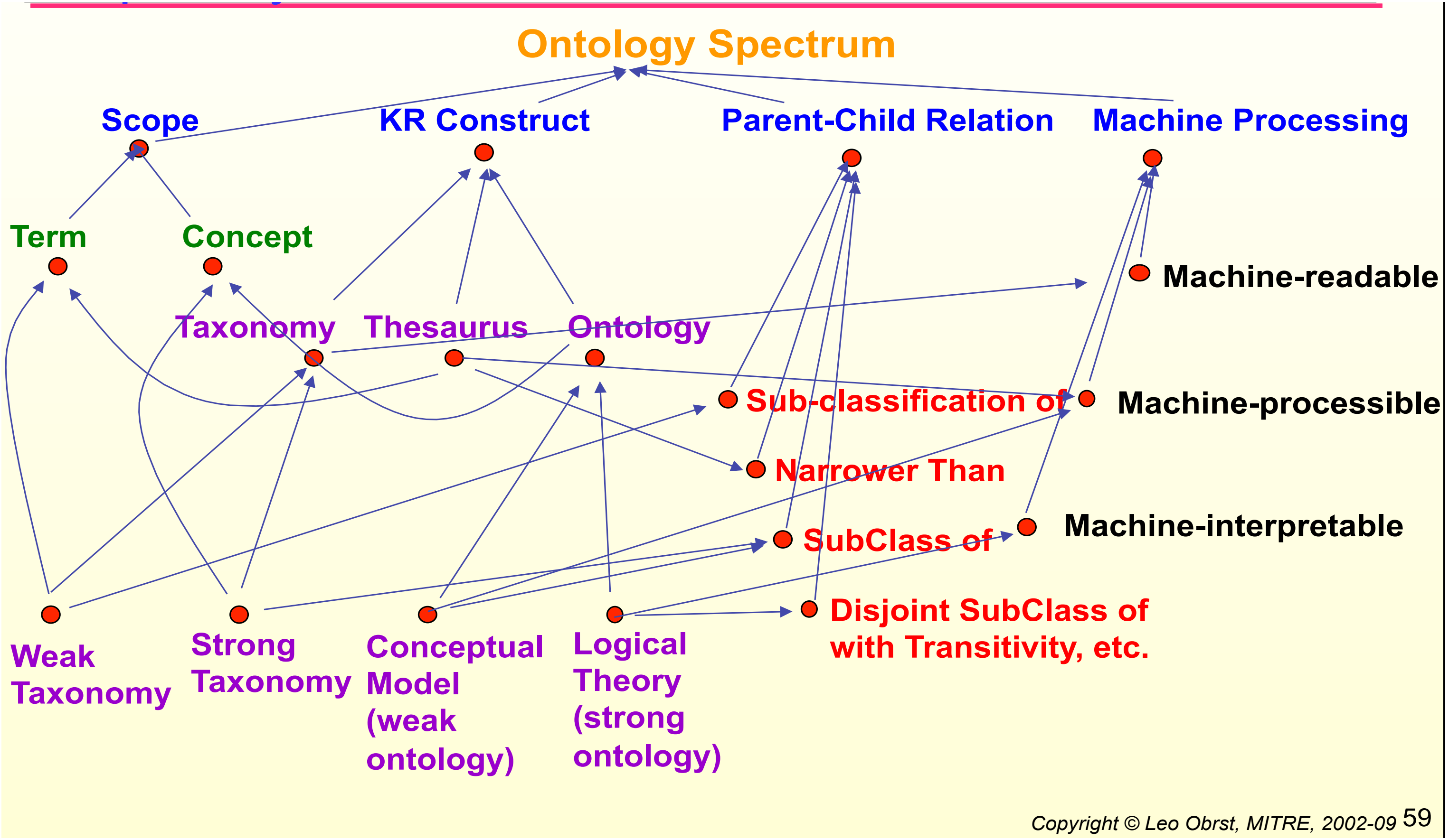


Mathematics
Logic
Philosophy
Enterprise Engineering
Industrial Engineering
Formal Methods
Linguistics
Business Management
Computer Science
Formal Semantics
Ontology
Database Theory
Sociology
Artificial Intelligence
Formal Ontology
Informal Ontology
Knowledge Management
Knowledge Representation
Conceptual Modeling
Ontology Engineering
Knowledge Engineering
Software/Data Engineering
Object Modeling


Ontology Spectrum
Scope
KR Construct
Parent-Child Relation
Machine Processing
Term
Concept
Machine-readable
Taxonomy
Thesaurus
Ontology
Sub-classification of
Machine-processible
Narrower Than
Machine-interpretable
SubClass of
Disjoint SubClass of with Transitivity, etc.
Weak Taxonomy
Strong Taxonomy
Conceptual Model (weak ontology)
Logical Theory (strong ontology)
Copyright © Leo Obrst, MITRE, 2002-09
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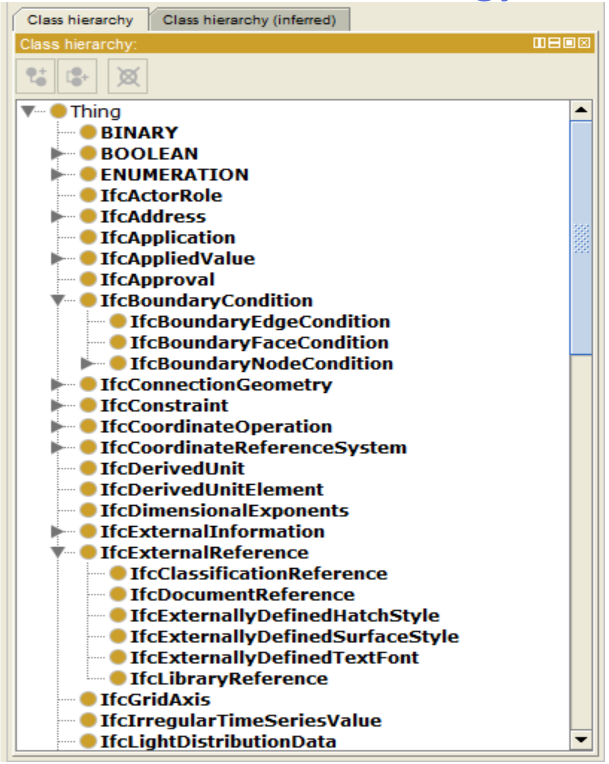
OWL Files !!

IFCowl: Is This an Ontology ?



Industry Foundation Classes

Formal or Informal ?

Classes defined in an OWL file are not usually an Ontology. !!

Logical Formalization

Is This an Ontology ?

Axiom 9: $WeldingProcess(w) \rightarrow PlannedProcess(w) \wedge \forall p\,(prescribedBy(w,p) \rightarrow WeldingSpecification(p))$

Axiom 10: $WeldingSpecification(p) \rightarrow JoiningSpecification(p) \wedge \forall f\,(hasContinuantPart(p,f) \rightarrow FusingMaterialActionSpecification(f)) \wedge \exists o\,(WeldingObjective(o) \wedge hasContinuantPart(p,o))$

Axiom 11: $ObjectiveSpecification(o) \wedge prescribes(o,j) \wedge WeldedJoint(j) \rightarrow WeldingObjectuve(p)$

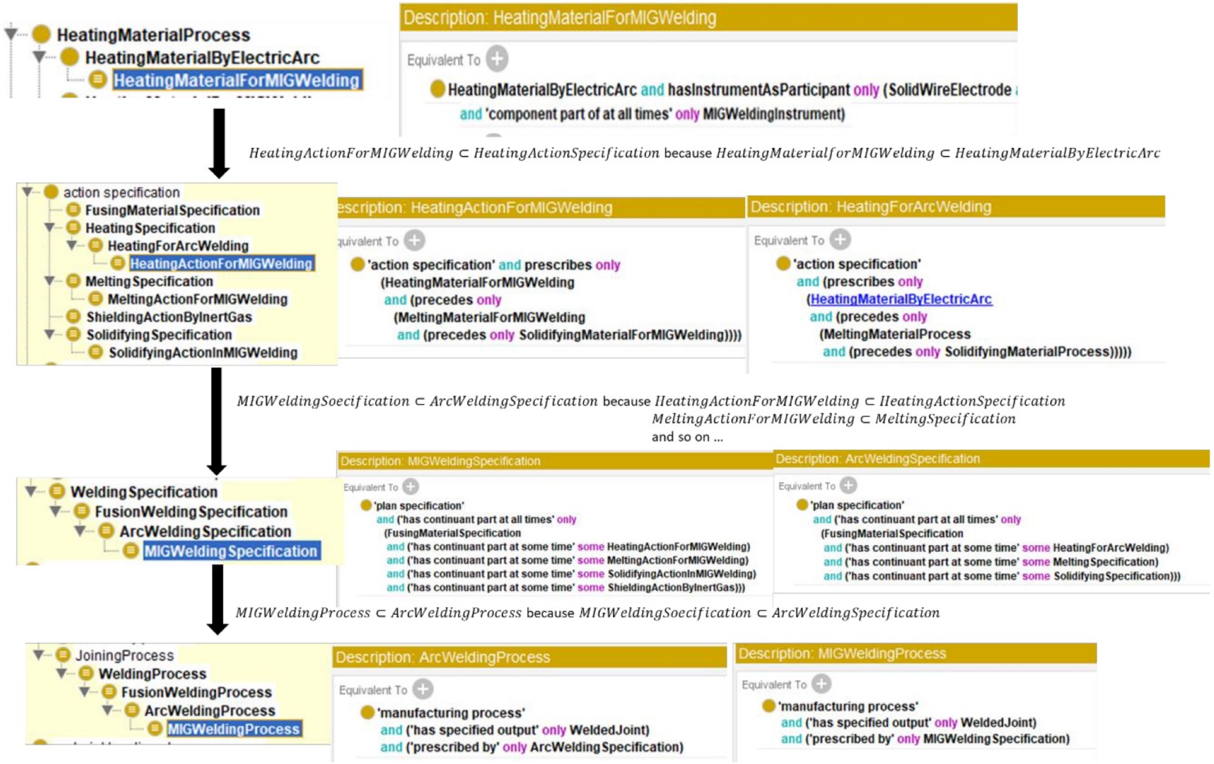
Axiom 12: $FusingMaterialActionSpecification(p) \rightarrow ActionSpecification(p) \wedge \exists h\,(HeatingActionSpecification(h) \wedge hasContinuantPart(p,h)) \wedge \exists mt\,(MeltingActionSpecification(mt) \wedge hasContinuantPart(p,mt)) \wedge \exists s\,(SolidifyingActionSpecification(h) \wedge hasContinuantPart(p,s))$

Axiom 13: $HeatingActionSpecification(p) \rightarrow ActionSpecification(p) \wedge \forall h \exists mt, s\,((prescribes(p,h) \rightarrow Heating(h) \wedge (Melting(mt) \wedge precedes(h,mt) \wedge (Solidifying(s) \wedge precedes(mt,s)))) \wedge \forall i\,(hasInstrument(h,i) \rightarrow WeldingMachine))$

Axiom 14: $MeltingActionSpecification(p) \rightarrow ActionSpecification(p) \wedge \forall mt \exists s\,((prescribes(p,mt) \rightarrow Melting(mt) \wedge (Solidifying(s) \wedge precedes(mt,s))) \wedge \forall c\,(hasPatient(mt,c) \rightarrow MaterialComponent(c) \vee FillerMaterial(c)))$

Axiom 15: $SolidifyingActionSpecification(p) \rightarrow ActionSpecification(p) \wedge \forall s\,((prescribes(p,s) \rightarrow Solidifying(s)) \wedge \forall g\,(environs(s,g) \rightarrow InertGas(g) \vee slug(g)) \wedge \forall c\,(hasPatient(s,c) \rightarrow MaterialComponent(c) \vee FillerMaterial(c)))$

Logical Formalization and the power of inference



Ontologies in Philosophy Vs Computer science

<u>Ontology perspective</u>

- **Representation** of entities, ideas, and events, their properties and relations, according to **a system of categories**.
- The **same** in Computer science and Philosophy.

<u>Ontology focus</u>

- In computer science, is about establishing fixed, controlled vocabularies.
- In philosophy, is more on the perception and the representation of the world.

In **computer science** and engineering area: **focusing** on the **formats of the vocabularies** (OWL, JSON, UML, etc.) and the **capacities to process** them.

Missing the most important part: The semantic disambiguation of the vocabulary.

Necessity to make the ***balance*** between the ***utility*** of use and the ***philosophical*** vision to represent the world when building ontologies.

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Ontology: From Conceptual model to Common Sense

What is termed Domain Ontology in the realms of artificial intelligence (including the Semantic Web) is a special type of conceptual model

The unfolding of formal ontology as a philosophical discipline aims at developing a system of general categories that can be used in the development of scientific theories and domain-specific common sense theories of reality.

(Guizzardi 2008)

Common Sense Knowledge

Basic ability to perceive, understand, and judge things that are shared by (‘common to’) nearly all people and can reasonably be expected of nearly all people without need for debate.”



- Manufacturing knowledge was defined as knowledge about manufacturing processes, assembly, quality, materials handling and operation planning.

Manufacturing Common Sense Knowledge contains know-how about the production process background knowledge, and experience from Machinist’s handbooks and validated shopfloor feedbacks.

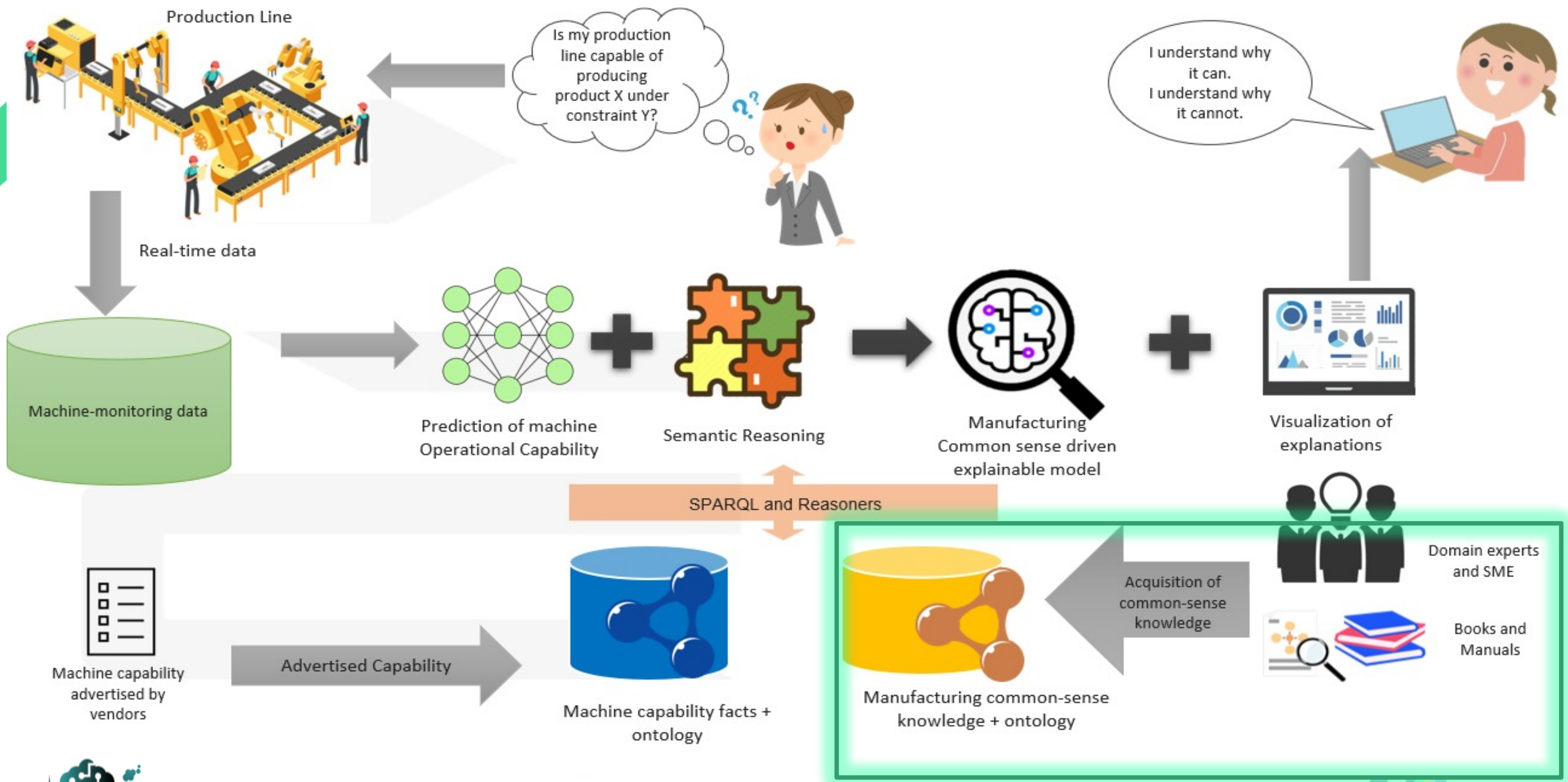
C. Rodosthenous, L. Michael, A hybrid approach to commonsense knowledge acquisition,in: STAIRS 2016, IOS Press, 2016, pp. 111–122

J. Tujillo, The DARPA Machine Common Sense (MCS) Program: A Phenomenological Diagnosis of its Interpretational Challenges, Infomotions, Incorporated, 2018, pp. 1–2

L.-J. Zang, C. Cao, Y.-N. Cao, Y.-M. Wu, C.-G. Cao, A survey of commonsense knowledge acquisition, Journal of Computer Science and Technology 28 (2013) 689–719.

F. Ilievski, A. Oltramari, K. Ma, B. Zhang, D. L. McGuinness, P. Szekely, Dimensions of commonsense knowledge, Knowledge-Based Systems 229 (2021) 107347.

L. He, P. Jiang, Manufacturing knowledge graph: a connectivism to answer productionproblems query with knowledge reuse, IEEE Access 7 (2019) 101231–101244.



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Manufacturing Common Sense Knowledge Graph

Augmented GenAI approach for building

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How should we build commosense Knowledge for Manufactuing

- **Where to find the knowldge ?**
  - Educational Institutions, Libraries and Archives, Research Journals and Conferences, Machinist Books and Publications, Work Experience
- **How to extract the knowldge ?**
  - Named Entity Recognition (NER),Relationship Extraction,Topic Modeling,Text Classification and summarization etc
- **How to Formalise the extracted knowldge ?**
  - Using Standard Vocabularies as such Manufacturing Domain
- **How to make knowledge useable ?**
  - Machine readble, machine interpretable, FAIR
- **How to store the extracted Knowledge?**
  - Dedicated portals, Open Knowldge Graphs, etc.

=> LLMs as a potential solution

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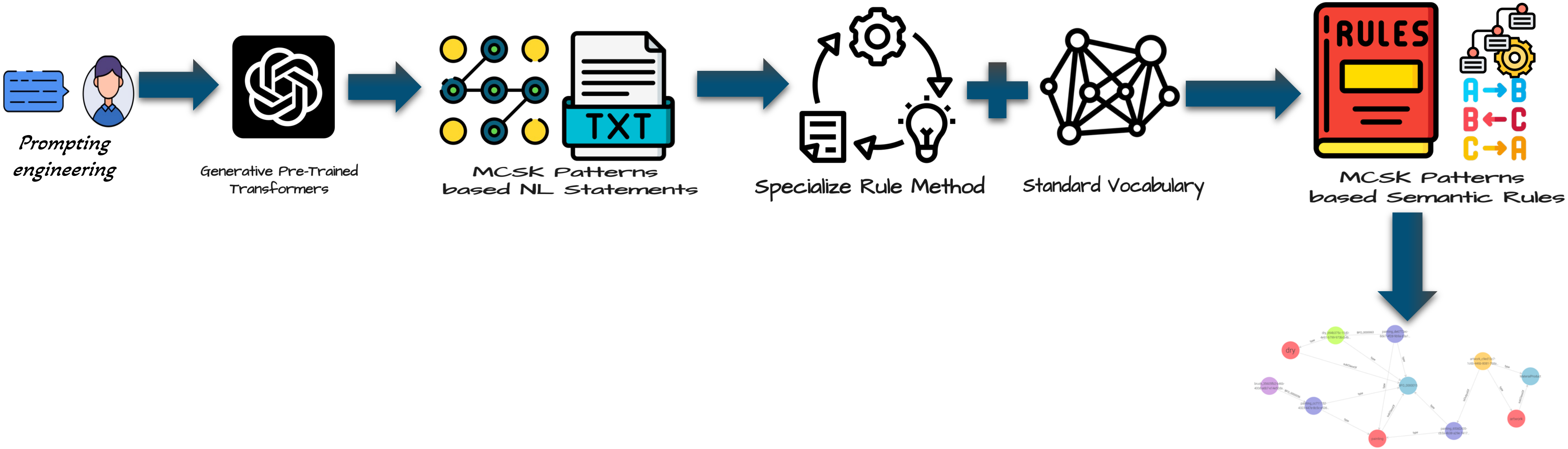
Limitations of pre-trained LLMs in the context of ontology development

- *Lack of Explicit Knowledge Representation*
- *Lack of logical consistency*
- *Semantic Ambiguity and inconsistent responses*
- *Domain Specificity*
- *Data Bias and Incompleteness*
- *Semantic Ambiguity*
- *Limited Multi-modal Understanding*
- *Scalability Issues*

MCSK Acquisition and Semantic Rules Generation Approach



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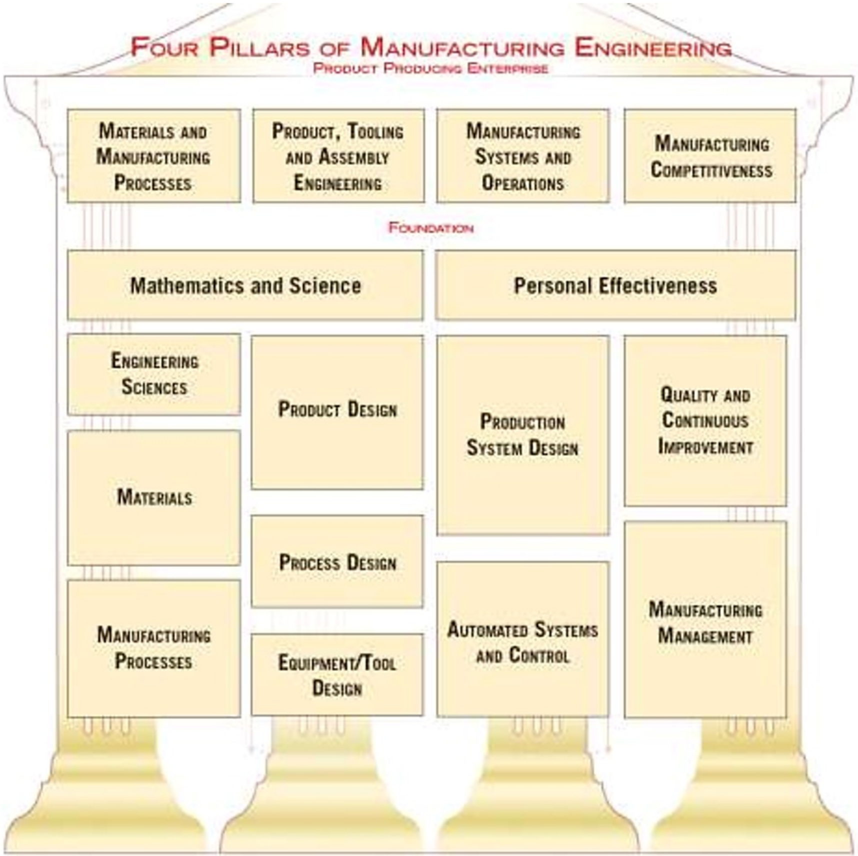
Identify MCSK Patterns

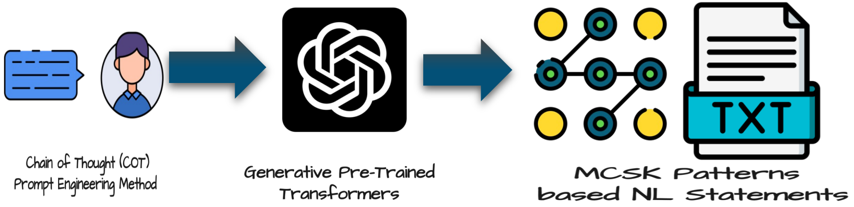


MCSK Patterns

1. Requirement
2. Precedence
3. Causation
4. Similarity
5. Distinctness
6. Parthood
7. Performance

Pahl G, Beitz W, Feldhusen J, et al. Engineering design: a systematic approach. Stud Q J 2010; 34(133): 63–64

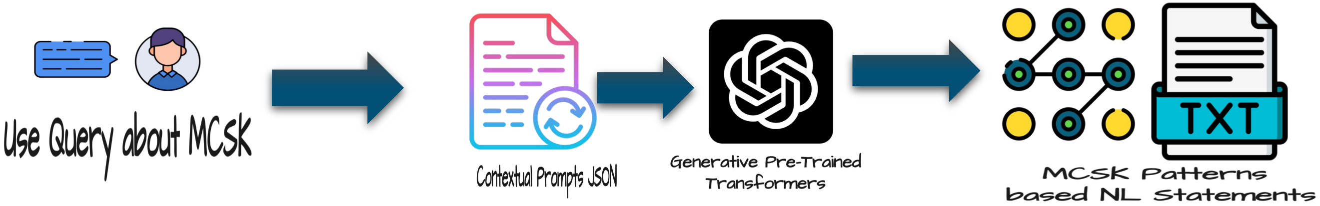
Extract MCSK using LLM



Chain of thought and Contextual prompt engineering

Utilize Open-AI API to extract MCSK according to identified patterns.

Extracted MCSK natural language (NL statements)



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MCSK as NL Statements

Pattern	Subcategory	Example
Requirement	Material Requirement	A wooden chair requires wood.
	Process Requirement	Cutting and assembling are required to manufacture a wooden chair.
	Tool Requirement	A saw is required to cut wood.
	Skill/Capability Requirement	The capability to cut and assemble wood properly.
	Environment/Location Requirement	A workshop is required for cutting and assembling the chair.
Precedence	Process Precedence	Designing the chair comes before cutting the wood.
	Object Precedence in Workflow	The wood must be present before it can be cut.
	Existence Precedence	The design of the chair must exist before the manufacturing process can begin.
Causation	Material Causation	Using low-quality wood causes the chair to be less sturdy.
	Process Causation	If the assembly process is not properly followed, the final chair might be unstable.
Similarity	Material Similarity	Both a wooden chair and a wooden bed require wood.
	Process Similarity	The cutting and assembling process is similar for a wooden chair and a wooden bed.
	Tool Similarity	Both processes require the use of a saw.
	Product Characteristic Similarity	Both a chair and a bed can be used for sitting.
	Environment Similarity	Both can be manufactured in a workshop.
Distinctness	Material Distinctness	A book is made with paper, a chair is made with wood.
	Process Distinctness	Printing and binding are required for making a book, while cutting and joining are required for making a chair.
	Requirement Distinctness	The requirements for making a book (e.g., print format, binding) differ from those for making a chair (e.g., type of wood, type of joinery).
Part-Hood	Process Part-hood	Cutting and joining are parts of the chair-making process.
	Object Part-hood	A chair consists of parts like legs, a backrest, and a seat.
	Grouping	A chair can be grouped with other types of furniture.
Performance	Material, Performance	High-quality wood, leads to a sturdy chair.
	Process Performance	Effective cutting and joining result in a well-made chair.
	Product Performance	A well-made chair offers comfortable seating.
	Environmental Performance	A well-ventilated and safety-compliant workshop leads to a safe and efficient production process.
	Competitive Performance	A well-made, well-priced chair can outperform competitors in the market.

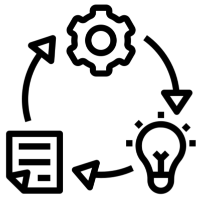
TXT

MCSK Patterns based NL Statements

Convert into Axiom
(First Order Logic)

MCSK Acquisition and Semantic Rules Generation Approach

Convert into First Order Logic



Function: *SpecializeRule*

Formally defined, the function SpecializeRule is:

$$\text{SpecializeRule} : RT \times MCSK \to CR$$

Process:

1. **Input**: A Rule Template, RT, and manufacturing Commonsense Knowledge, $MCSK$.
2. **Extraction**: Identify and extract specific classes or instances from the $MCSK$.
3. **Substitution**: Systematically replace the placeholders in RT with the extracted classes/instances.
4. **Output**: Return a Concrete Rule, CR.

RT =Rule Template
MCSK= Manufacturing Commonsense Knowledge in NL
CR=Concrete Rule

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MCSK Acquisition and Semantic Rules Generation Approach

Convert into Axiom
(First Order Logic)

Definition 1: Rule Template

In logic, a Rule Template (RT) is like a formula where you fill in the blanks. The formula isn't complete on its own because some parts are left blank. You can fill in these blanks with specific information later on, which will turn the template into a rule that can be used in certain situations. A Rule Template, RT, is defined as a logical expression containing placeholders that represent general classes or relationships. These placeholders are meant to be replaced with specific classes or instances to create a concrete Rule.The **x** and **y** are place holders fro specfic processes.

Example:

$$\text{process}(x) \rightarrow \exists y \text{process}(y) \wedge \text{precedes}(x,y) \quad (1)$$

MCSK Acquisition and Semantic Rules Generation Approach

Convert into Axiom (First Order Logic)

Definition 2: Common Sense Knowledge (CSK)

A CSK is an NL statement that provides specific Knowledge about a particular case, like classes or instances regarding Painting extracted from LLM using the Chain of thought prompt engineering method. The CSK serves as the source from which specific information is extracted to replace placeholders in the Rule Template.

Example: "The result of painting process is a painted object."

Example: "After painting process, you do drying process."

Example: "The drying process involves a dryer machine."

MCSK Acquisition and Semantic Rules Generation Approach

Convert into Axiom (First Order Logic)

Definition 3: Concrete Rule

A Concrete Rule, CR, is derived from a Rule Template by replacing its placeholders with specific classes or instances extracted from a MCSK.

Function: *SpecializeRule*

Formally defined, the function SpecializeRule is:

$$\text{SpecializeRule} : RT \times MCSK \rightarrow CR \tag{2}$$

MCSK Acquisition and Semantic Rules Generation Approach

Convert into Axiom
(First Order Logic)

Rule Given the Rule Template, RT:

$$\text{process}(x) \rightarrow \exists y \text{process}(y) \wedge \text{comesafter}(\text{y,x})$$

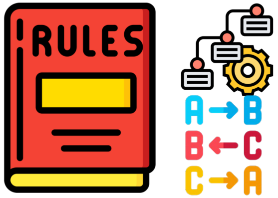
MA-CSK:"After painting process, you should perform a drying process."

Applying SpecializeRule:

$$\text{drying}(x) \rightarrow \exists y \text{painting}(y) \wedge \text{comesafter}(\text{y,x})$$

MCSK Acquisition and Semantic Rules Generation Approach

Convert into Semantic Rule

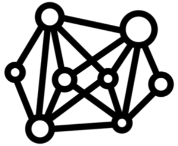


MCSK Patterns based Semantic Rules

- **Alignment with Standard Vocabularies**
- **Use of Existing Relation**
- **Mapping Process (driven by predefined mapping rules)**
- **Conversion to Query Languages**

MCSK Acquisition and Semantic Rules Generation Approach

Convert into Semantic Rule



Standard Vocabulary

Given the Rule Template, RT:

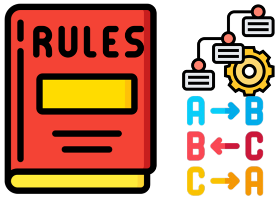
$$\text{BFO:process}(x) \rightarrow \exists y \text{BFO:process}(y) \wedge \text{BFO:precedes(y,x)}$$

Extracted MACSK NL Statement :“After painting Process perform drying Process”

Applying SpecializeRule:

$$\text{drying}(x) \rightarrow \exists y \text{painting}(y) \wedge \text{BFO:precedes(y,x)}$$

Convert into Semantic Rule



MCSK Patterns based Semantic Rules

Rule 1

Given the Rule Template, *RT* based on Standard vocabulary classes and property relations from BFO and IOF:

$$\text{IOF:MaterialProduct}(x) \rightarrow \exists y \text{BFO:process}(y) \wedge \text{IOF:isOutputof(x,y)} \quad (3)$$

CSK: "The result of painting is a painted object."

Applying *SpecializeRule*:

$$paintedobject(x) \rightarrow \exists y \text{painting}(y) \wedge \text{IOF:isOutputof (x,y)} \quad (4)$$

Rule 2

Given the Rule Template, *RT*:

$$\text{BFO:process}(x) \rightarrow \exists y \text{BFO:process}(y) \wedge \text{BFO:precedes(x,y)} \quad (5)$$

CSK:"After painting, you should dry."

Applying SpecializeRule:

$$\text{drying}(x) \rightarrow \exists y \text{painting}(y) \wedge \text{BFO:precedes(x,y)} \quad (6)$$

Rule 3

Given the Rule Template, *RT*:

$$\text{BFO:process}(x) \rightarrow \exists y \text{IOF:machine}(y) \wedge \text{BFO:participates in at some time (y,x)} \quad (7)$$

CSK: "The drying process involves a dryer machine."

Applying *SpecializeRule*:

$$\text{drying}(x) \rightarrow \exists y \text{dryer}(y) \wedge \text{BFO:participates in at some time (y,x)} \quad (8)$$

Université de Technologie Tarbes Occitanie Pyrénées

Manufacturing Common Sense Knowledge Graph

The generated semantic rules are then in a graph-based structure.

MACS-KG

Benefits of Graph-Based Storage:

- Graphs naturally represent entities and relationships, allowing more intuitive data manipulation and quicker access."
- Enables direct querying of specific entities or relationships without the need to traverse unnecessary paths, significantly enhancing performance.

Operational Framework:

- Semantic rules converted from MCSK are stored as nodes and edges in MACS-KG, with nodes representing processes or terms and edges representing relationships like 'precedes'.
- Whenever a query is made, only the relevant subgraph is retrieved, minimizing data handling and processing time.


MACS-KG

KGA a platform for collaboration and networking

❖**Knowldge Graph Alliance** nonprofit organization

❖KGA *ACTs as a bridge among the ongoing and future efforts by industry, research organizations, universities, and standardization bodies in SKG to facilitate harmonization, benchmarking, and standardization along with the development of industry-standard guidance, maturity, and risk models for alleviating the uncertainty of the return of industrial investment in SKG transition projects.*

❖KGA *showcases the practical use of state-of-the-art and future technologies as part of its continuous promotional effort in building confidence in companies for adoption* of SKG in their operations.

www.kg-alliance.org

Conclusions

- Symbolic & Neurosymbolic Explanation are required for industrial trust and adoption
  - It’s not a matter of compete it’s a matter of complete
- We need XAI enablers such as Common Sense Knowledge
- Common Sense and Logics should be driven by a hybrid approach: acquiring through Bottom-up and Building from top down
- Explainability in AI is also a matter of knowledge and abstraction not only a matter of algorithms