IFAC
INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL

INCOM 2021 BUDAPEST

Integration and Interoperability in Automated and Smart Manufacturing Systems

F.B. Vernadat

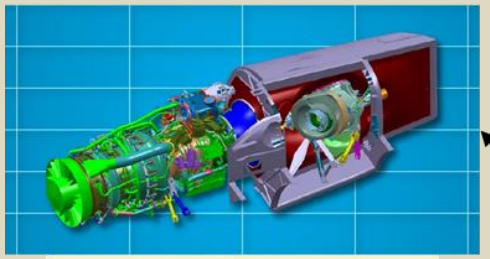
LGIPM, University of Lorraine, Metz, France

Retired HoU from EU Institutions, Luxemburg

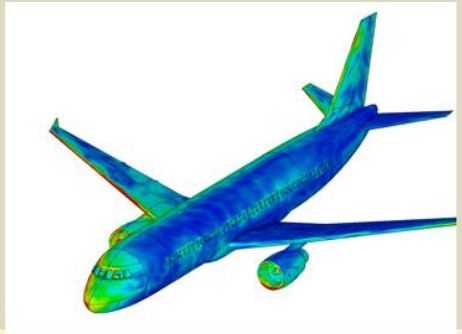
lgipm Laboratoire de Génie Industriel, de Production et de Maintenance

UNIVERSITÉ DE LORRAINE

Context: From Computer-Integrated Manufacturing (CIM)…



Computer-Aided Design



Computer-Aided Engineering

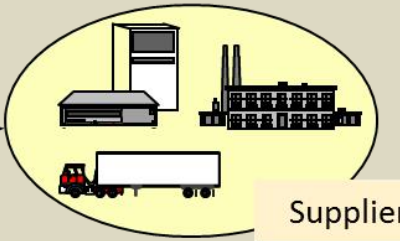
ERP / CRM

Product Data Management

Intranet

Internet

Extranet



Suppliers

Final Assembly Plant

lgipm

UNIVERSITÉ DE LORRAINE

… to highly global business environments

- Global business environments:
  - ICT platforms to support information sharing & collaboration
  - Aligned organizational structures and processes to support collaborative work involving different functional groups
  - Compatible vision and values as well as complementary competencies and capabilities
- Smart Manufacturing / Industry 4.0:
  - Cyber-physical systems, IIoT, Manufacturing-as-a-Service (MaaS), applied Artificial Intelligence & Machine Learning, Big Data

=> Strong need for Systems Integration and Interoperability

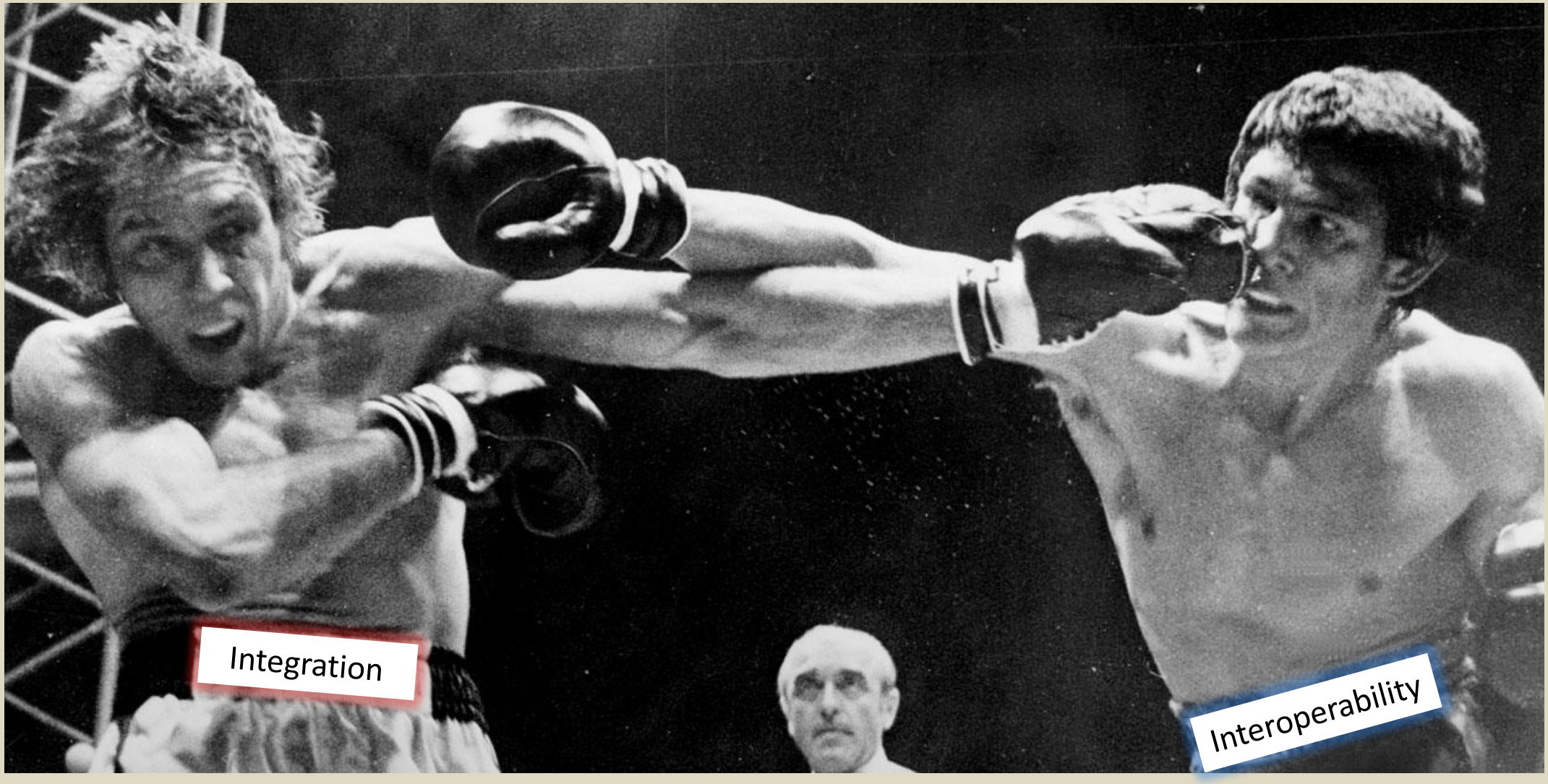
IFAC
INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL

INCOM 2021 BUDAPEST

2 I's and the 4 C's

- Integration (Ig) & Interoperability (Ip)

- Communication, Coordination, Cooperation & Collaboration

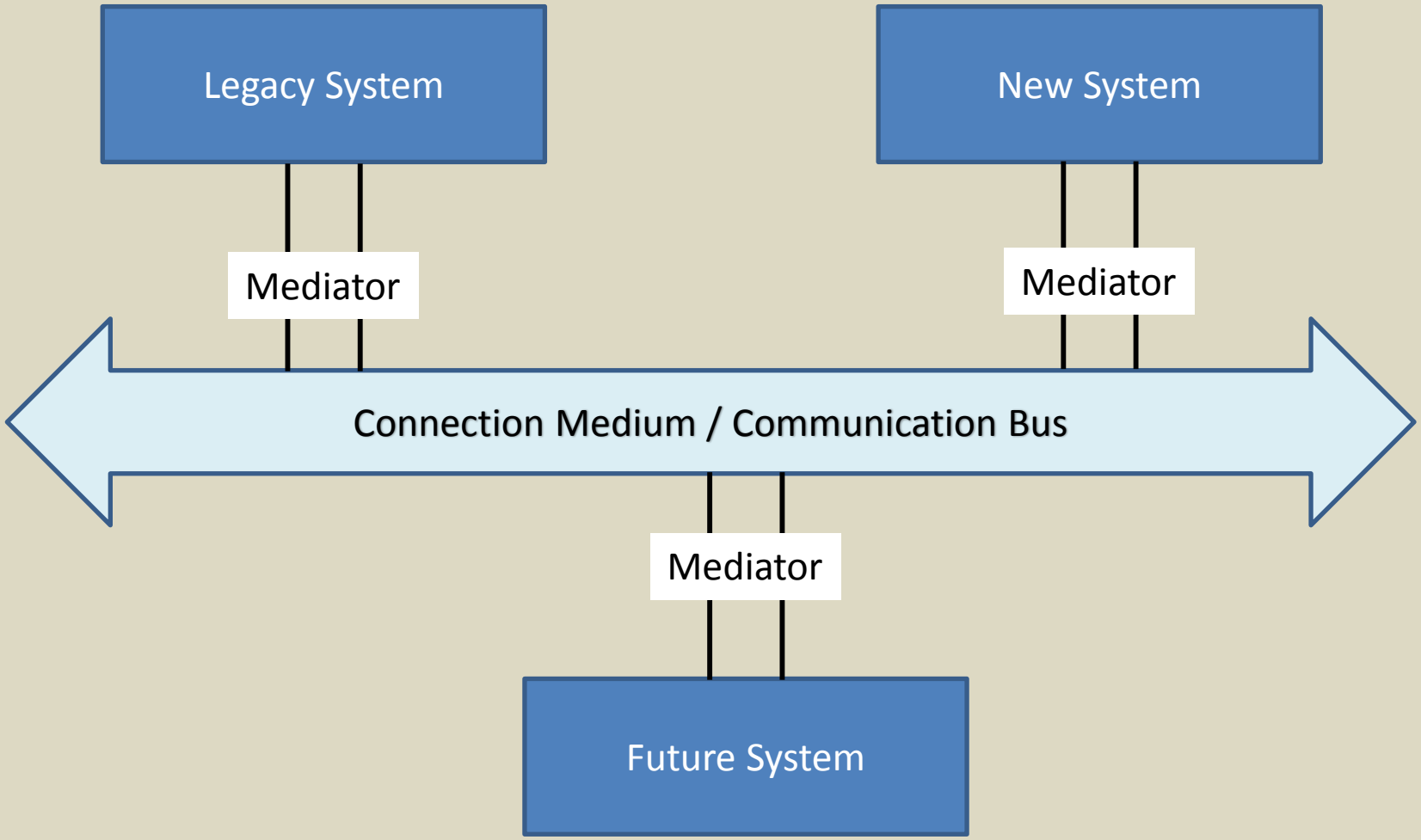

Integration
Interoperability


Integration
Interoperability

Integration & Interoperability: What for?

- Fundamentally, to enable (heterogeneous or foreign) systems to "talk" to one another and to "work" with each other
- To overcome:
  - Siloed environments
  - Interchange needs / Collaboration requirements
  - Heterogeneous systems
  - Incompatible solutions
  - Language / legislation / regulation / legal barriers
  - …

Distributed System Interplay Principle



Historical Overview in Manufacturing

	Manufacturing Integration Need Evolution	ICT Solution Evolution
70's	CAD/CAM interfacing CAD/CAPP/CAM integration FMS (NC machines, robots, conveyors, AS/AR syst.)	Computer networks Dedicated interfaces /APIs Synchronization by PLC's
80's	CIM (ICAM, IPAD, CAM-I, ESPRIT), CAE Just-in-time / Kanban	Distributed computing, Shared databases / SQL IGES / SET / STEP, EDI/EDIFACT TCP/IP, MAP, TOP
90's Y2K	Concurrent Engineering (CE), EE / VE Enterprise Integration, ERP, MES, SCADA, PDM Agile Manufacturing, Global Supply Chains	OOP (Java, C++, C#, VB…), Client-server architecture CORBA / OSF-DCE / ODP, COM/DCOM, Workflow Eng. XML, HTTP/S, HTML, UML, PSL
2000's	Collaborative Networked Organization (CNO) eBusiness (B2B, B2C), eWork, eServices PLM, Green Mfg, Sustainable Mfg	SOA, JEEE / .Net, SOAP, EJB, Web Services, MDA JMS/MOM/ESB, Enterprise Portals / Portlets, EAI, BPEL Semantic Web / OWL, Virtualization, Cloud computing
2010's	Cloud Manufacturing, Virtual Manufacturing Smart Manufacturing / Industry 4.0 Smart Products, Digital Twins, CPS	IoT / IoS / IoE, RFID, Wi-Fi, IPv6, 4G/5G Micro-servers, Micro-services, Ind. Internet Platf. (IIPs) Product / Manufacturing ontologies, IOF
2020's	Industry 5.0, …	Big Data Analytics, Blockchains Deep learning, AR, VR, …

Historical Overview in Manufacturing

	Manufacturing Integration Need Evolution	ICT Solution Evolution
70's	CAD/CAM interfacing CAD/CAPP/CAM integration FMS (NC machines, robots, conveyors, AS/AR syst.)	Computer networks Dedicated interfaces / APIs Synchronization by PLC's
80's	CIM (ICAM, IPAD, CAM-I, ESPRIT), CAE Just-in-time / Kanban	Distributed computing, Shared databases / SQL IGES / SET / STEP, EDI/EDIFACT TCP/IP, MAP, TOP
90's	Concurrent Engineering (CE), EE / VE Enterprise Integration, ERP, MES, SCADA, PDM	OOP (Java, C++, C#, VB…), Client-server architecture CORBA / OSF-DCE / ODP, COM/DCOM, Workflow Eng.
Y2K	Agile Manufacturing, Global Supply Chains	XML, HTTP/S, HTML, UML, PSL
2000's	Collaborative Networked Organization (CNO) eBusiness (B2B, B2C), eWork, eServices PLM, Green Mfg, Sustainable Mfg	SOA, JEEE / .Net, SOAP, EJB, Web Services, MDA JMS/MOM/ESB, Enterprise Portals / Portlets, EAI, BPEL Semantic Web / OWL, Virtualization, Cloud computing
2010's	Cloud Manufacturing, Virtual Manufacturing Smart Manufacturing / Industry 4.0 Smart Products, Digital Twins, CPS	IoT / IoS / IoE, RFID, Wi-Fi, IPv6, 4G/5G Micro-servers, Micro-services, Ind. Internet Platf. (IIPs) Product / Manufacturing ontologies, IOF
2020's	Industry 5.0, …	Big Data Analytics, Blockchains Deep learning, AR, VR, …

Historical Overview in Manufacturing

	Manufacturing Integration Need Evolution	ICT Solution Evolution
70's	CAD/CAM interfacing CAD/CAPP/CAM integration FMS (NC machines, robots, conveyors, AS/AR syst.)	Computer networks Dedicated interfaces / APIs Synchronization by PLC's
80's	CIM (ICAM, IPAD, CAM-I, ESPRIT), CAE Just-in-time / Kanban	Distributed computing, Shared databases / SQL IGES / SET / STEP, EDI/EDIFACT TCP/IP, MAP, TOP
90's	Concurrent Engineering (CE), EE / VE Enterprise Integration, ERP, MES, SCADA, PDM	OOP (Java, C++, C#, VB…), Client-server architecture CORBA / OSF-DCE / ODP, COM/DCOM, Workflow Eng.
Y2K	Agile Manufacturing, Global Supply Chains	XML, HTTP/S, HTML,
2000's	Collaborative Networked Organization (CNO) eBusiness (B2B, B2C), eWork, eServices PLM, Green Mfg, Sustainable Mfg	SOA, .Net, SOA, Web Services, M JM B, Enterprise Portals / Portlets L Semantic Web / OWL, Virtualization, Cloud computing
2010's	Cloud Manufacturing, Virtual Manufacturing Smart Manufacturing / Industry 4.0 Smart Products, Digital Twins, CPS	IoS / IoE, RFID, Wi-Fi, IPv6, 4G/5G Micro-servers, Micro-services, In erne (IIPs) Product / Manufacturing ontologies, IOF
2020's	Industry 5.0, …	Big Data Analytic cha Deep learning, AI

Dedicated solutions
Monolithic architectures
Open standards
Open source software (OSS)
Model-Driven Architectures (MDA)

F.B. Vernadat

Integration & Interoperability: What is it?

(Webster and Oxford dictionaries)

- To integrate:
  - *"To make whole or complete"*
  - *"To put parts together to form a synergistic whole"*

    (applies to data, systems, processes, organizations and people)

- To interoperate:
  - "The *ability of a system to use parts of another system"*

    (mostly applies to systems and processes)

Enterprise Integration

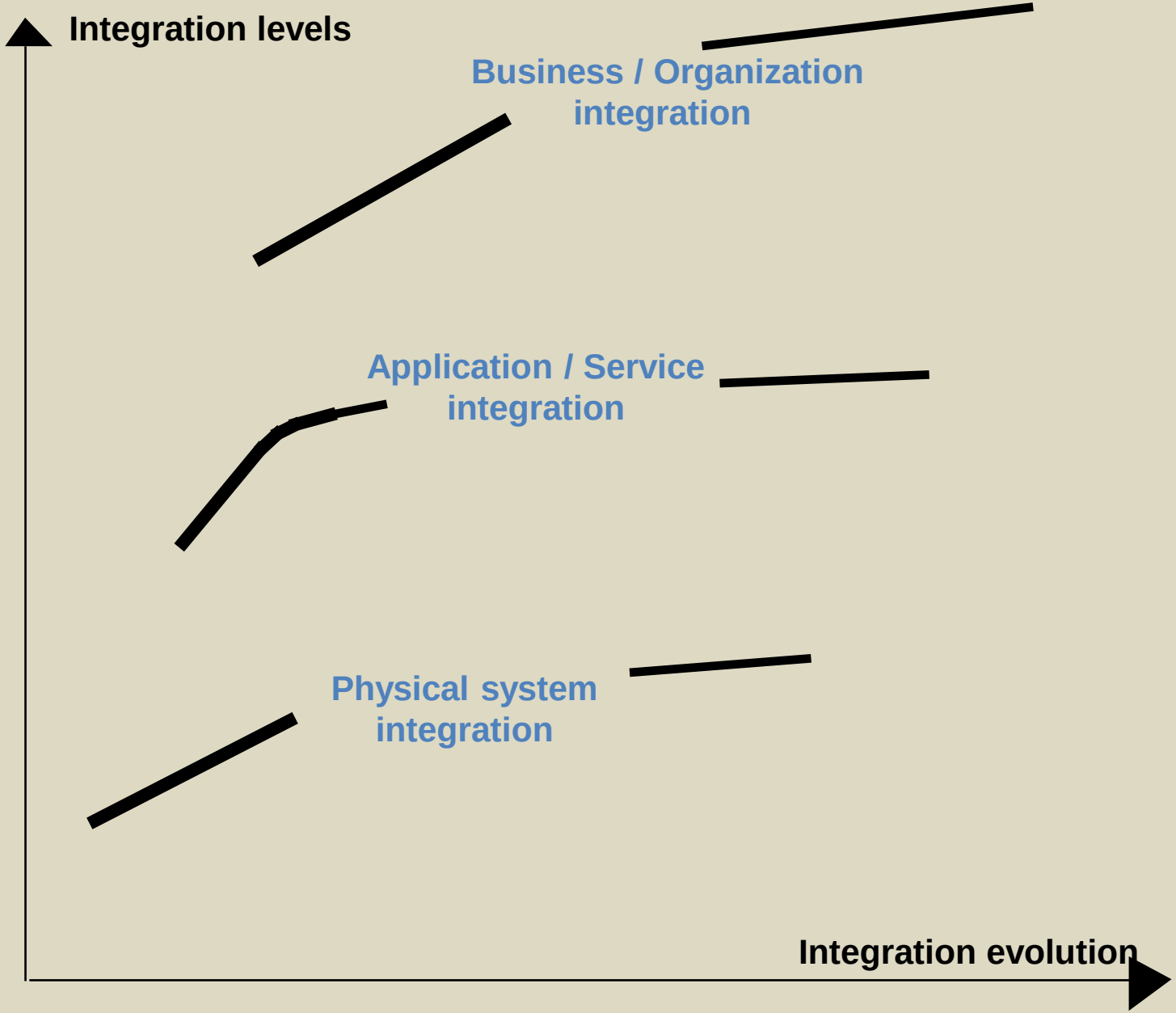
- Deals with removing barriers between people, machines and applications to enhance **synergy** within an enterprise (or a network of enterprises) to better achieve business objectives (or **mission**) (Vernadat, 1996)

  Challenge: The right information at the right place at the right time

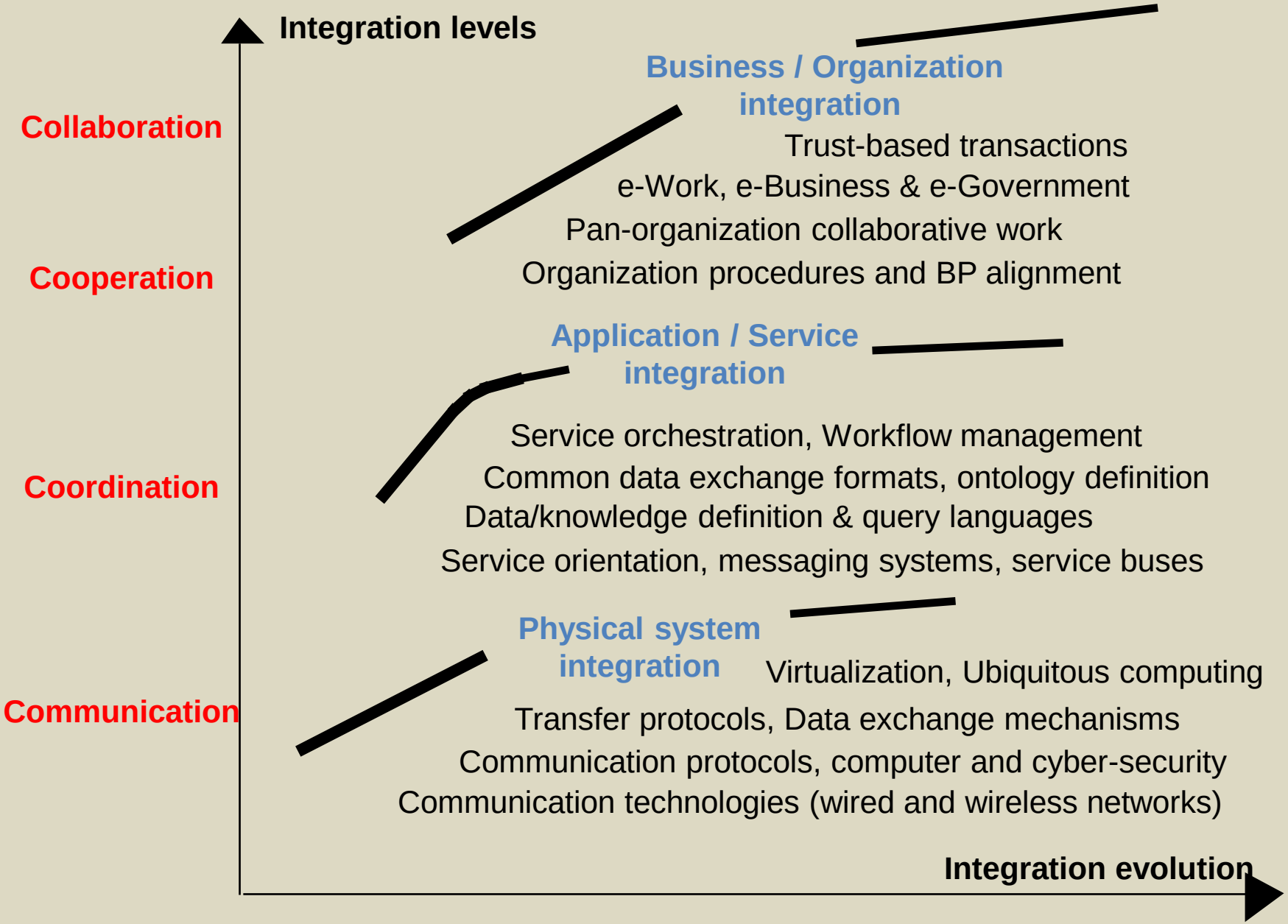
- Is the **coordination** of all elements including business processes, people, and technology of the enterprise **working together** in order to achieve the optimal fulfillment of the mission of that enterprise as defined by enterprise management (Williams and Li, 1999)

  Strong organizational dimension in addition to technological dimension

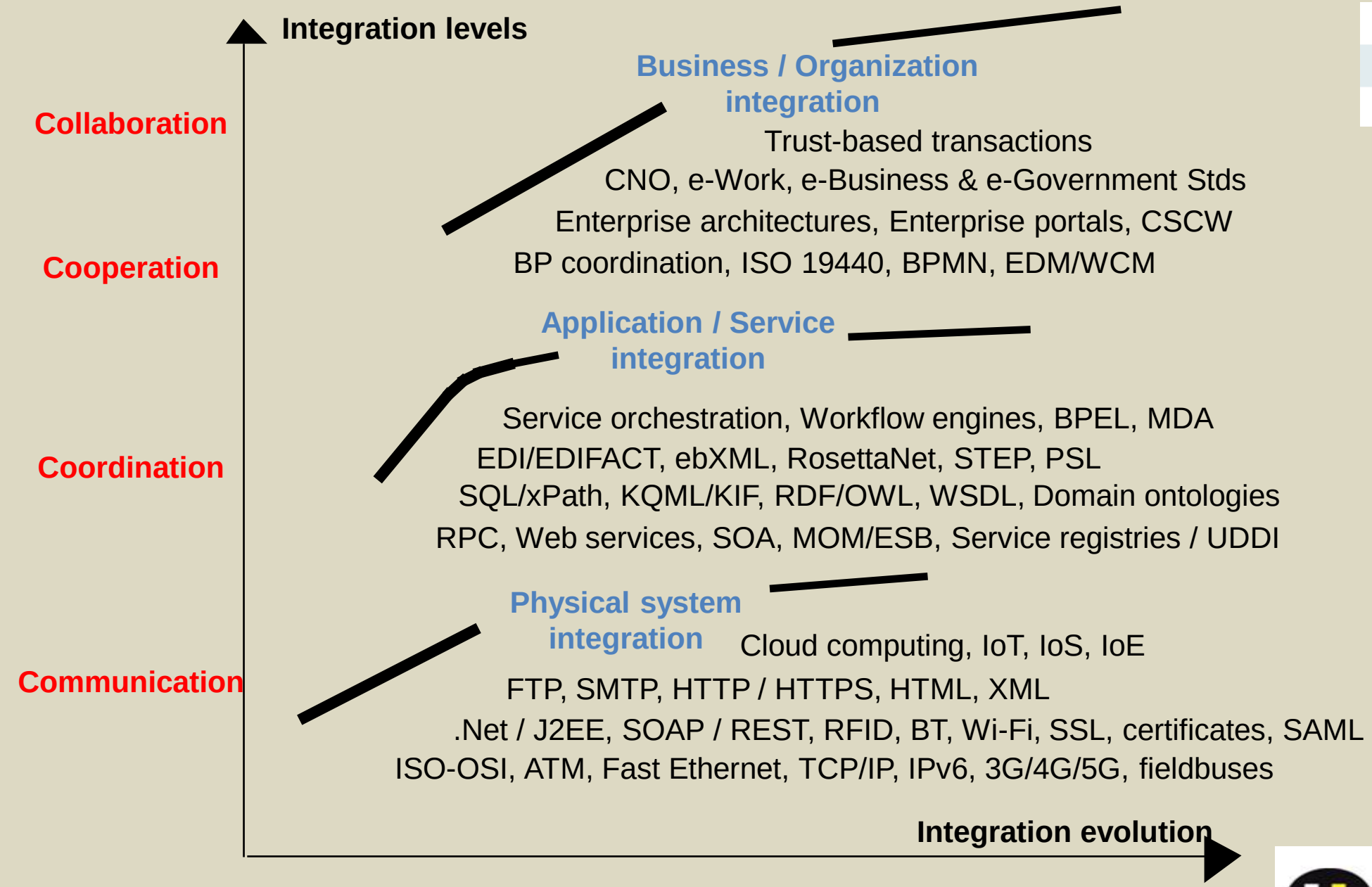
  EI drivers: communication, co-ordination, co-operation and collaboration



(AMICE, 1991, Rev. 2021)



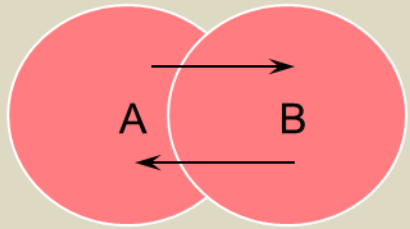
(AMICE, 1991, Rev. 2021)


Integration levels
Collaboration
Cooperation
Coordination
Communication
Business / Organization integration
Trust-based transactions
CNO, e-Work, e-Business & e-Government Stds
Enterprise architectures, Enterprise portals, CSCW
BP coordination, ISO 19440, BPMN, EDM/WCM
Application / Service integration
Service orchestration, Workflow engines, BPEL, MDA
EDI/EDIFACT, ebXML, RosettaNet, STEP, PSL
SQL/xPath, KQML/KIF, RDF/OWL, WSDL, Domain ontologies
RPC, Web services, SOA, MOM/ESB, Service registries / UDDI
Physical system integration
Cloud computing, IoT, IoS, IoE
FTP, SMTP, HTTP / HTTPS, HTML, XML
.Net / J2EE, SOAP / REST, RFID, BT, Wi-Fi, SSL, certificates, SAML
ISO-OSI, ATM, Fast Ethernet, TCP/IP, IPv6, 3G/4G/5G, fieldbuses
Integration evolution

Degrees of integration

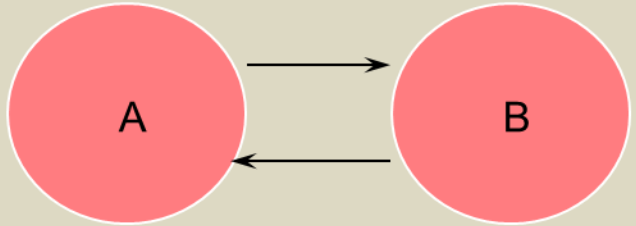
STAND ALONE

. Elements make their own decisions
. No communication between elements



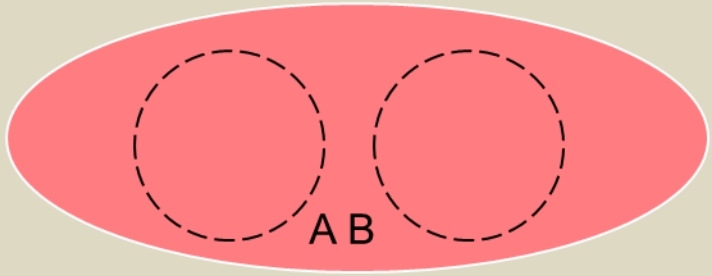
TIGHTLY INTEGRATED

. Make decisions for combined benefit
. Two way communication between elements



INTERFACED / LOOSELY COUPLED

. Make decisions for own benefit
. One or two way communication



UNITED / FULLY INTEGRATED

. No individual decision making
. Centralised control
. Single database

Different types of system integration

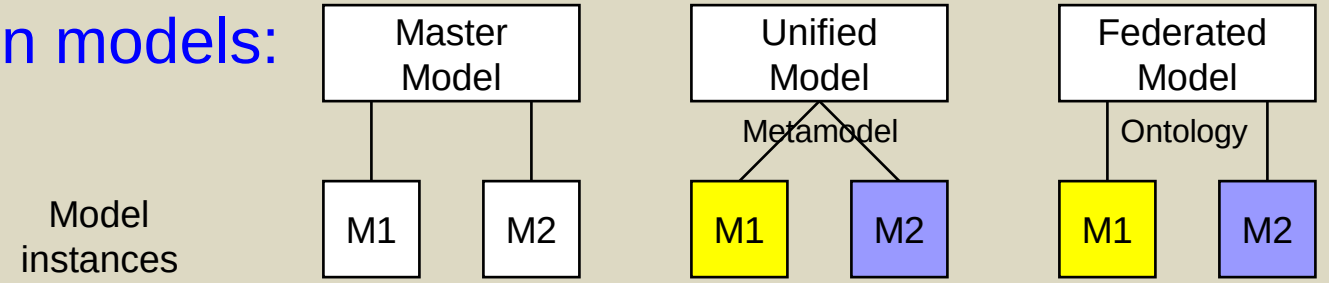
F.B. Vernadat

Integration vs. Interoperability

- Types of integration:
  - **Intra-enterprise integration** vs. **Inter-enterprise integration**
  - **Vertical integration** (within one functional domain) vs. **Horizontal integration** (across functional domains) vs. **End-to-end** integration

- Semantic unification: concept alignment space (the hardest challenge)

- Integration models:



(ICEIMT, 1991)

Interoperability = Loosely coupled integration

(i.e. each system component preserves its autonomy)

Systems Interoperability

- **IT Definition:** "the ability of two or more systems or components to exchange information and to use the information that has been exchanged"

(IEEE, 1991)

- **SE Definition:** "the ability of a system or process to seamlessly use information **and/or** functionality of another system or process by adhering to common (open) standards"

To inter-operate: to work together and understand information exchanged

Enterprise Interoperability

- Enterprise Interoperability: to provide two or more business entities with the ability of exchanging or sharing information and/or using functionality of one another with minimal effort (Athena EU Project, 2005)

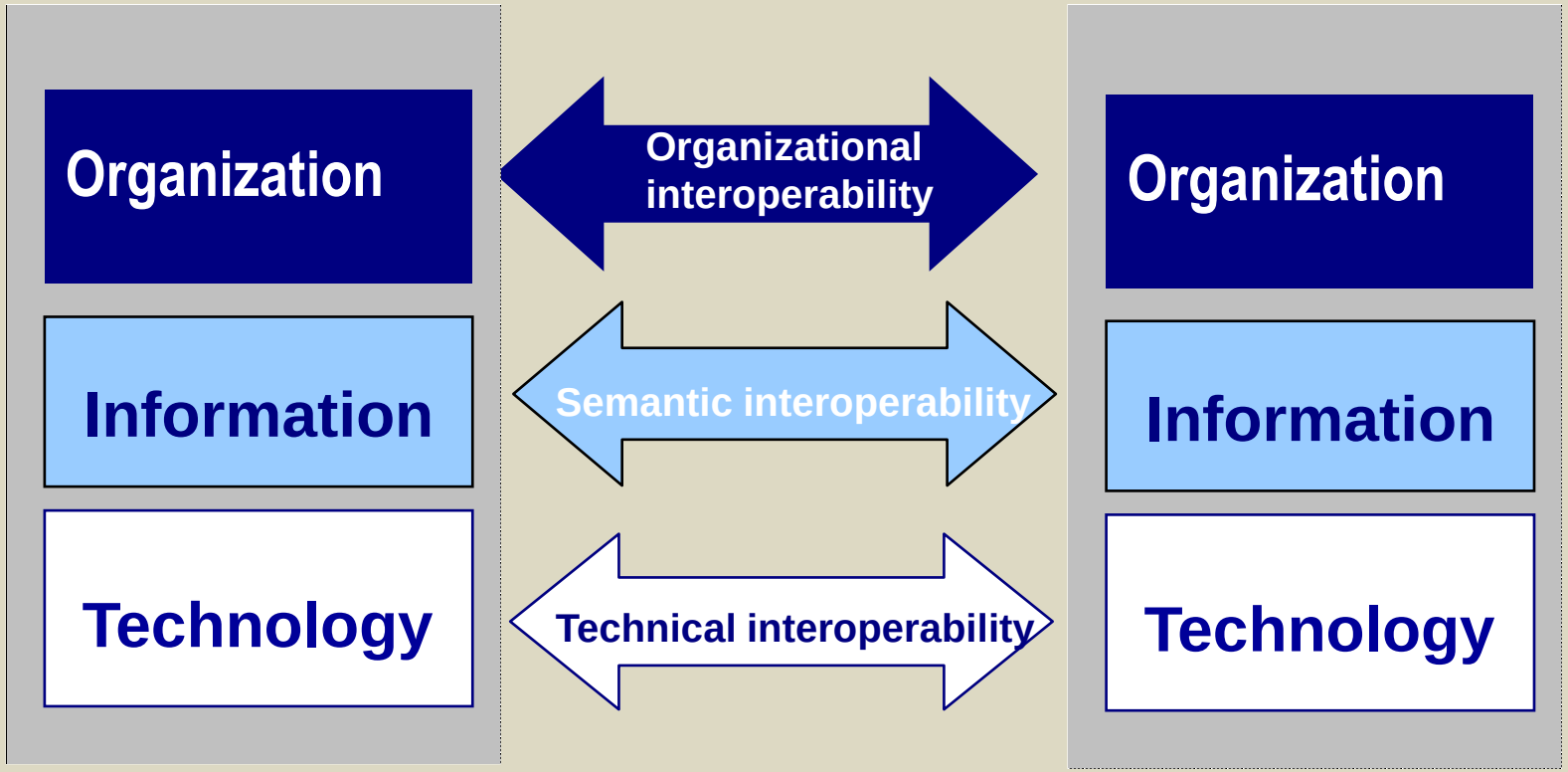
- Interoperable enterprise systems: offer greater flexibility and use less monolithic approaches than integrated systems

Ig & Ip Frameworks

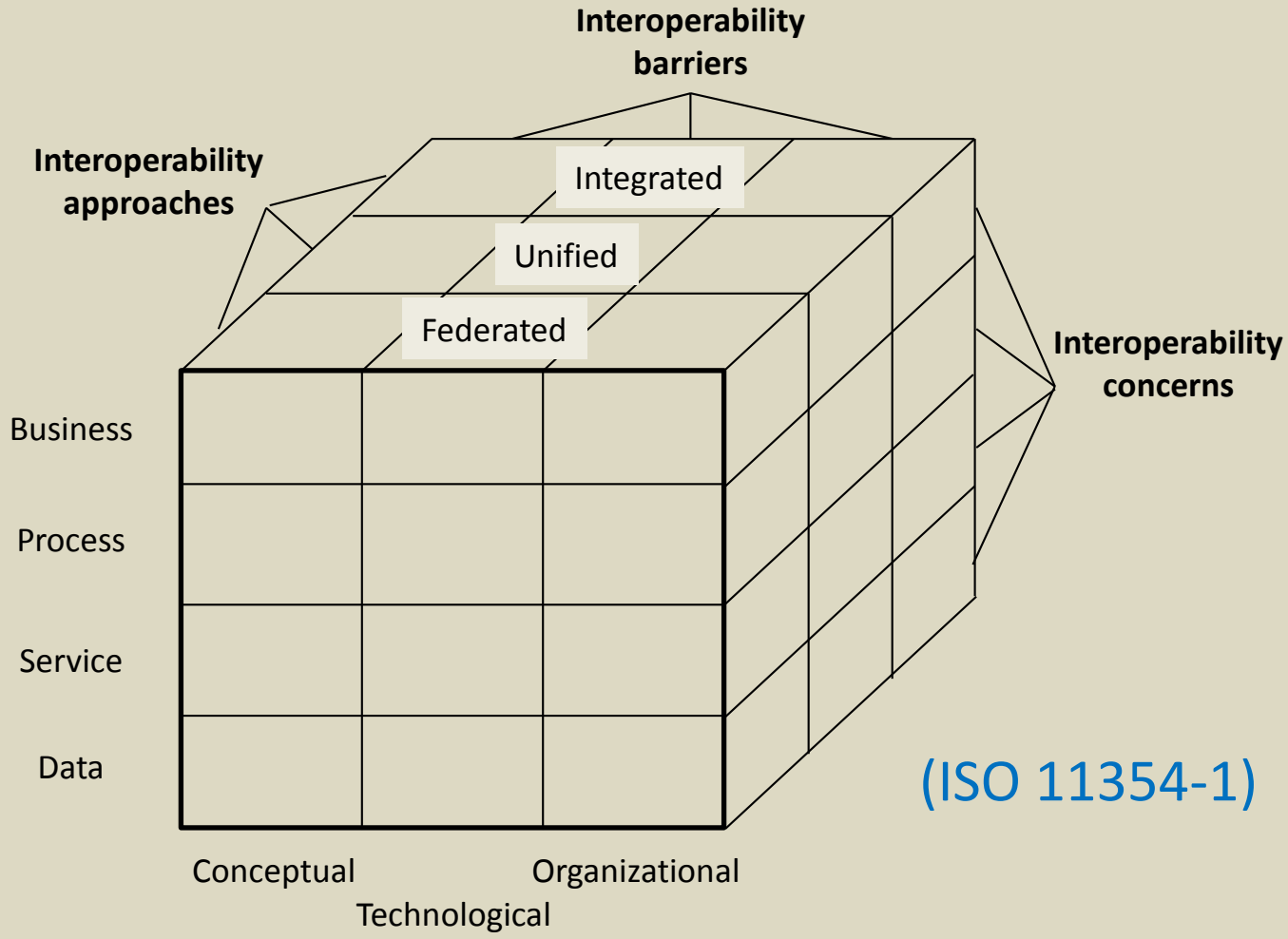
- Enterprise Integration Frameworks
  - CIMOSA, PERA, GRAI-GIM, TOVE…
  - Generalized into GERAM (1999) by IFAC-IFIP Task Force (-> ISO 15704)
- Enterprise Interoperability Frameworks

- The LISI Reference Model: levels of information systems interoperability (C4ISR US DoD, 1998)
- LCIM: The Levels of Conceptual Interoperability Model (Tolk, 2003)
- The ATHENA Interoperability Framework (AIF) (2005)
- E-Health Interoperability Framework by NEHTA, AU and i2-Health (EU)
- Federated Interoperability Framework (FIF) - dedicated to aerospace PLM (since 2007)
- …
- The Framework for Enterprise Interoperability (D. Chen & INTEROP-NoE, 2007)
- EU's European Interoperability Framework (EIF) (EU IDABC, since 2004)

Dimensions of Interoperability



The Framework for Enterprise Interoperability (FEI)



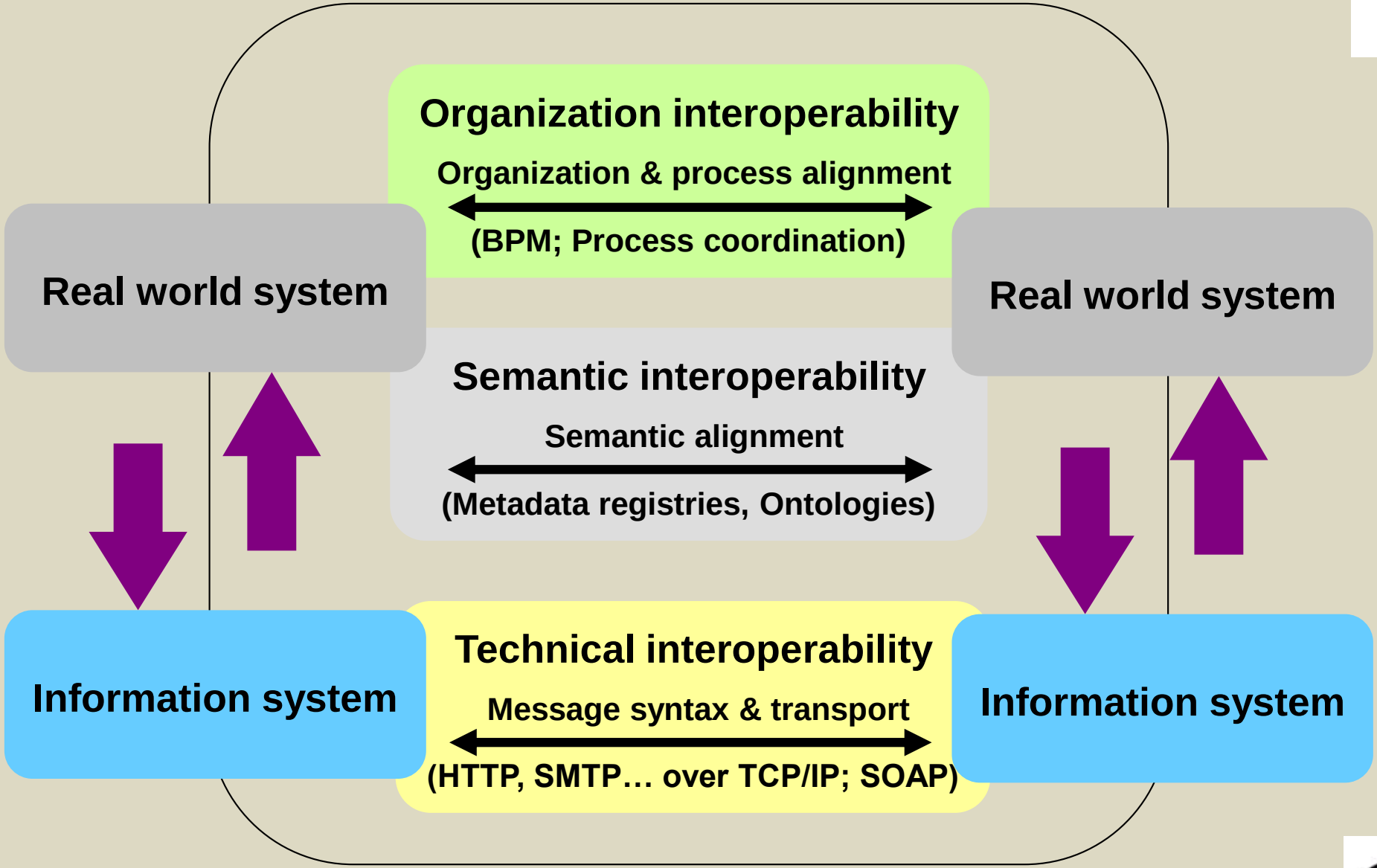
(ISO 11354-1)

Related topics:

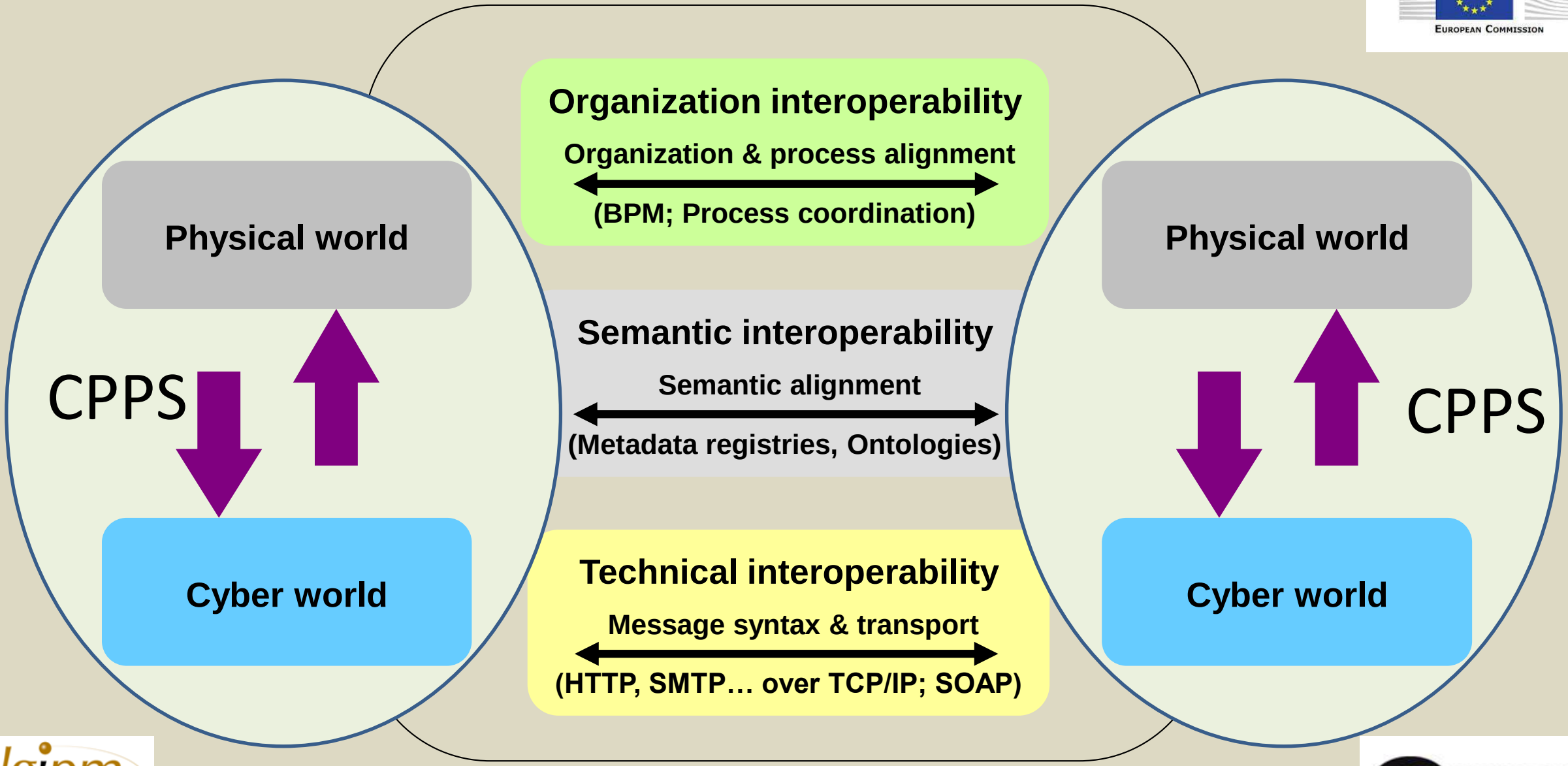
- Interoperability Maturity Models
- Interoperability Capability Models
- Interoperability Assessment (INAS)
- Interoperability project management
- …

(See Guédria, Naudet, Chen, Ducq, Panetto, Jardim-Goncalvez, Tolk, Ford, Cestari, Weichhart et al. Whitman …)

European Interoperability Framework (EIF)



EIF and I4.0 / Smart Manufacturing



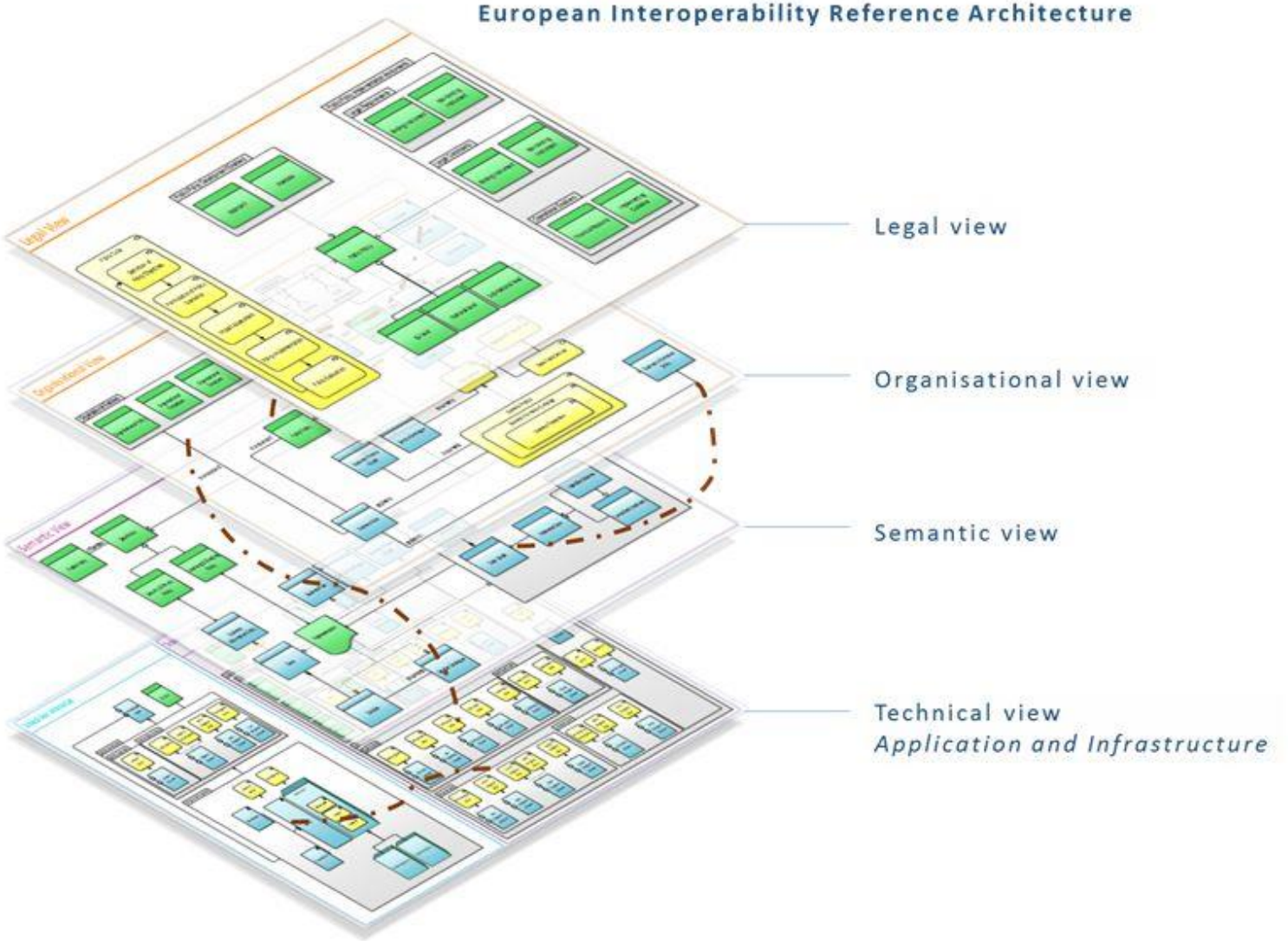
EIRA
Overview

European Commission

1 2 3

European Commission

European Interoperability Reference Architecture



lgipm Laboratoire de Génie Industriel, de Production et de Maintenance

UNIVERSITÉ DE LORRAINE

Some Solutions for I4.0 / Smart Manufacturing

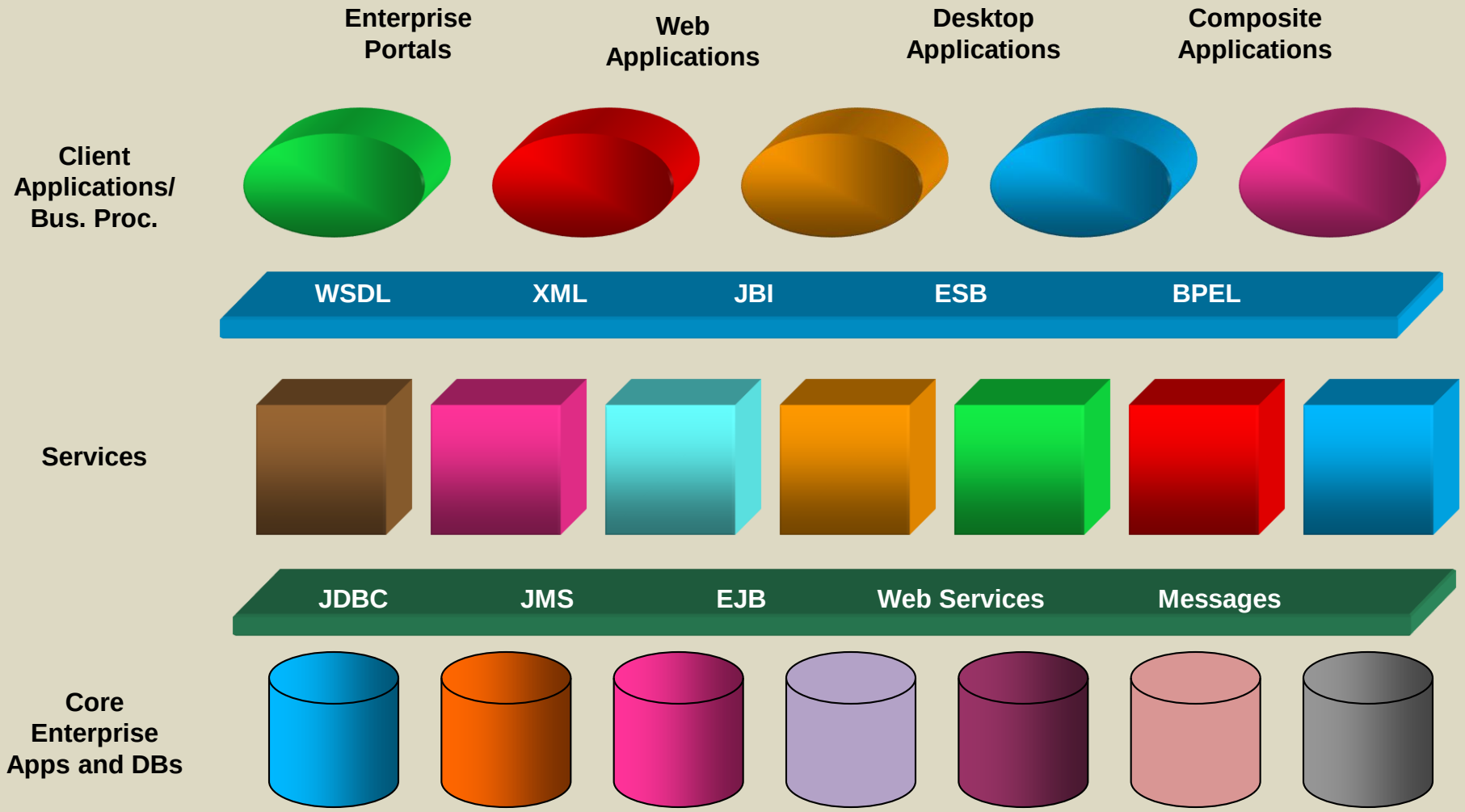
- **Technical level** (connection and communication)
- **Semantic level** (communication)
- **Organization level** (coordination/cooperation/collaboration)

Technical Level

Obj.: To send/receive data/information and messages (requests/replies)

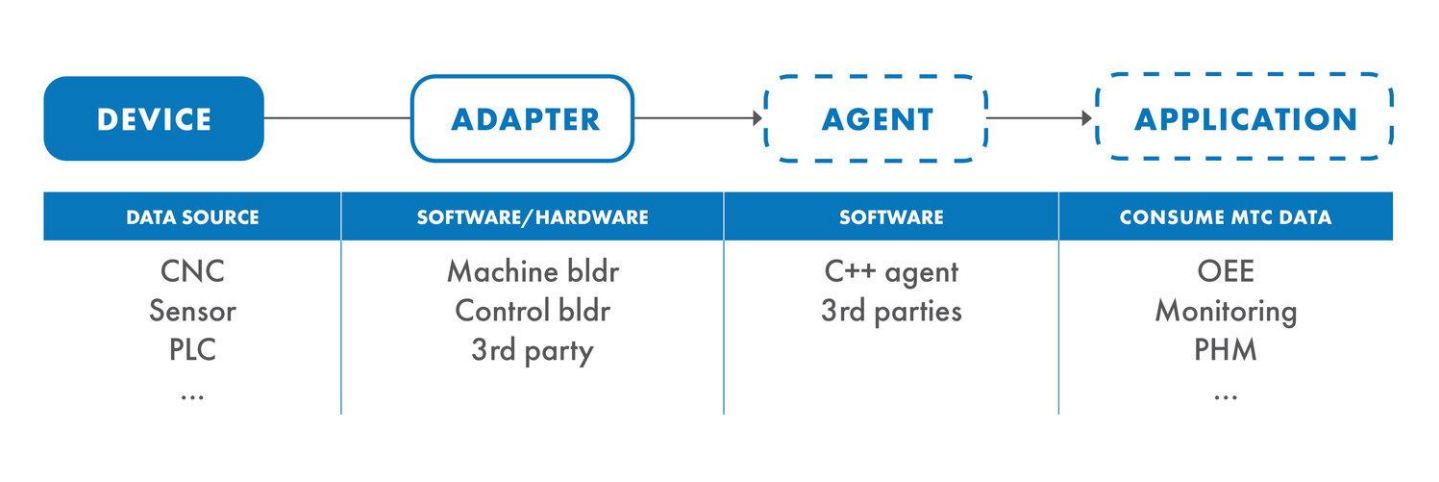
- **TCP/IP, HTTP/S and XML** open standards revolution (1995) with Service-Oriented Architecture (**SOA**) and **Web Services** (2000's)
- **MTConnect** (ANSI MTC1.4-2018)
- **OPC-UA** (OPC Unified Architecture)
- **IIoT**, Micro-Web servers and **Connected Objects**

SOA (using J2EE tech.)

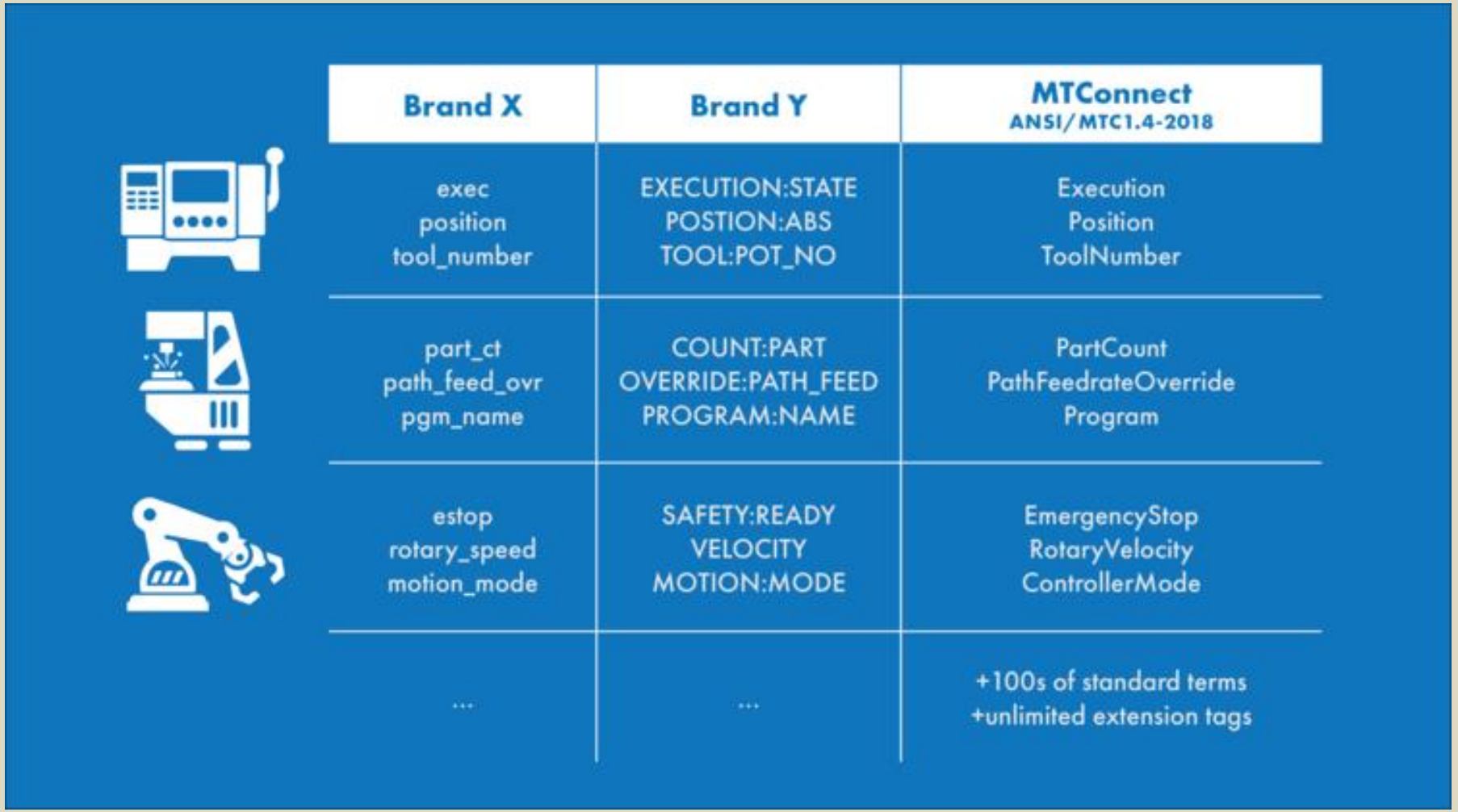


MTConnect

- ANSI/MTC1.4-2018 (last version 1.7, 2021)
- Facilitates data exchange between devices (sensors, control devices, shopfloor equipement and tools or software applications)
- Provides normalized domain-specific vocabulary and data models for mfg devices
- Made of data tags and behavior specifications of adapter agents for devices
- MTConnect devices output data in XML via HTTP servers



MTConnect Example



Brand X	Brand Y	MTConnect ANSI/MTC1.4-2018
exec position tool_number	EXECUTION:STATE POSTION:ABS TOOL:POT_NO	Execution Position ToolNumber
part_ct path_feed_ovr pgm_name	COUNT:PART OVERRIDE:PATH_FEED PROGRAM:NAME	PartCount PathFeedrateOverride Program
estop rotary_speed motion_mode	SAFETY:READY VELOCITY MOTION:MODE	EmergencyStop RotaryVelocity ControllerMode
...	...	+100s of standard terms +unlimited extension tags

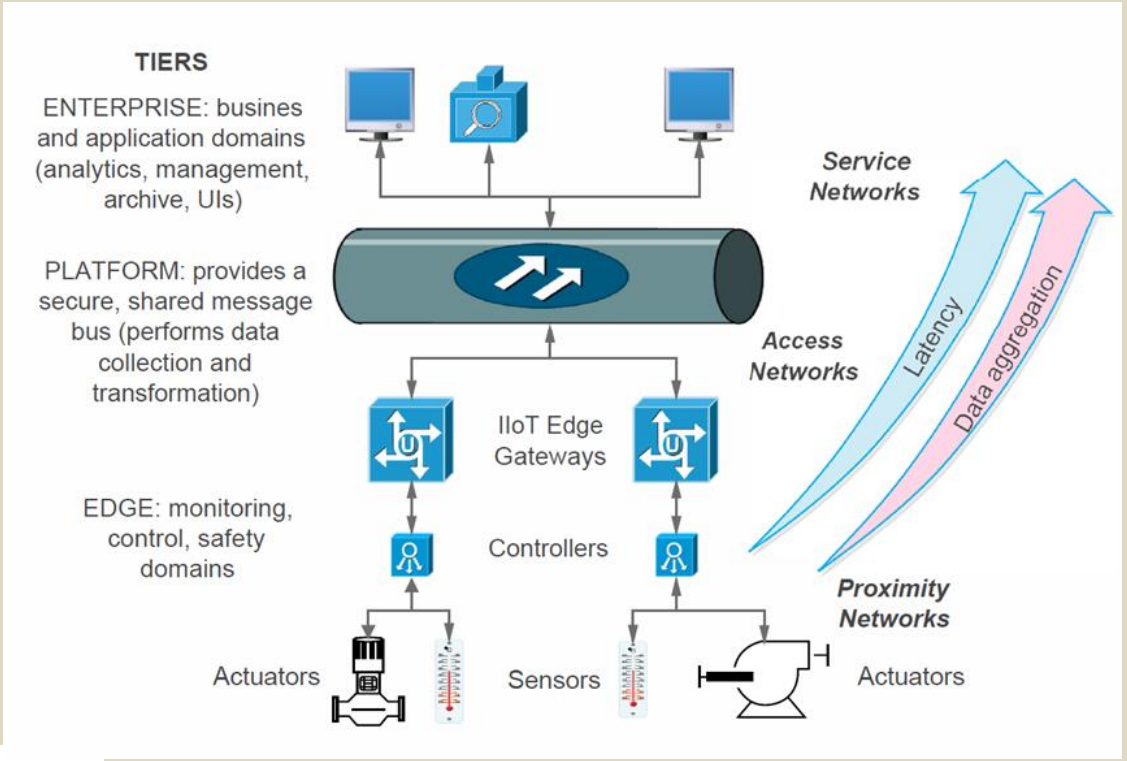
OPC-UA

- Open Platform Communication – Unified Architecture
- By OPC Foundation
- OPC-UA is an interoperability standard for the secure and reliable exchange of data in the industrial automation space and in other industries
- Evolved from OPC Classic (based on MS COM/DCOM)
- Is a platform independent service-oriented architecture (SOA) and ensures the seamless flow of information among devices from multiple vendors
- Is a series of specifications developed by industry vendors, end-users and software developers

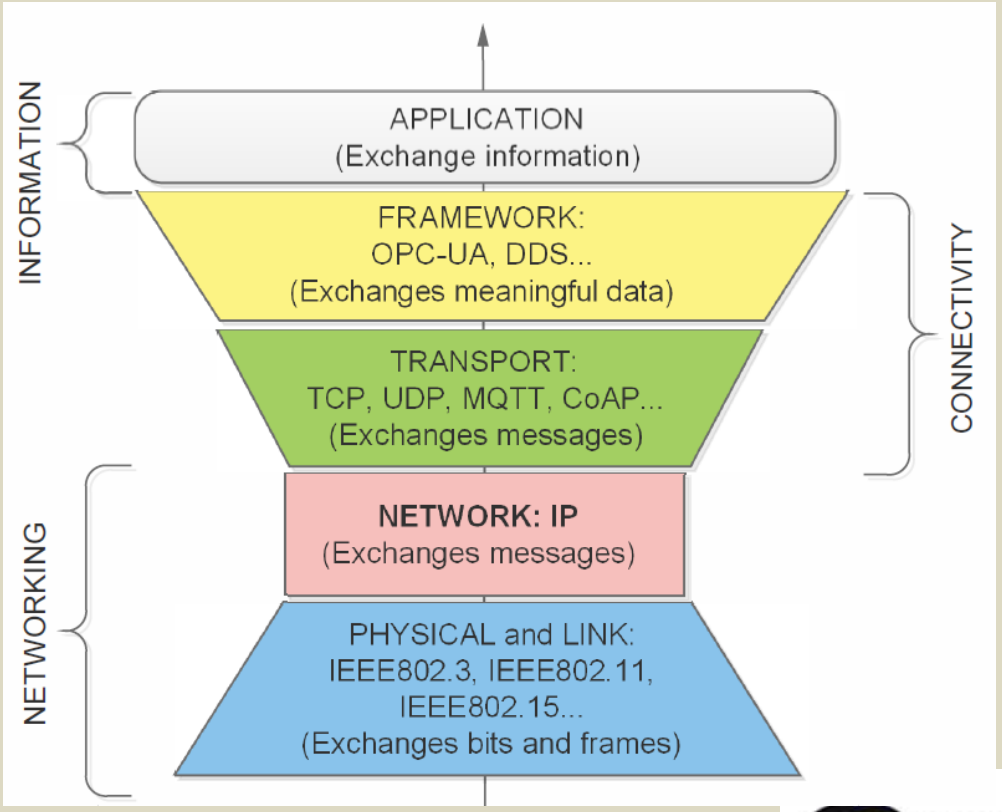
IEC 62541

IIoT (Industrial IoT)

- IoT is a computing concept describing ubiquitous connection to the Internet, turning common objects into connected objects
- IoT has made possible the CPS (Cyber-Physical System) paradigm



3-tier IIoT architecture (Sisinni et al., 2018)



IIoT protocol stack

Micro-Web servers and Connected Objects

Micro-Web Servers: two kinds:

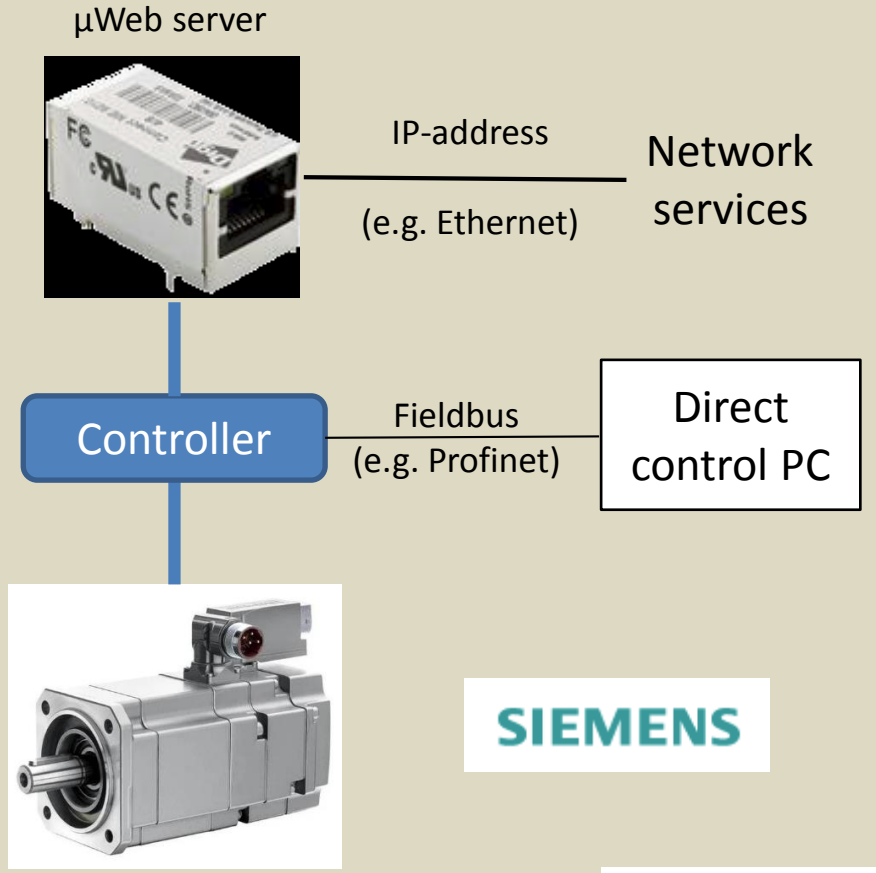
- Software: e.g. TinyWeb by Ritlabs
- Hardware:

Micro-Web servers and Connected Objects

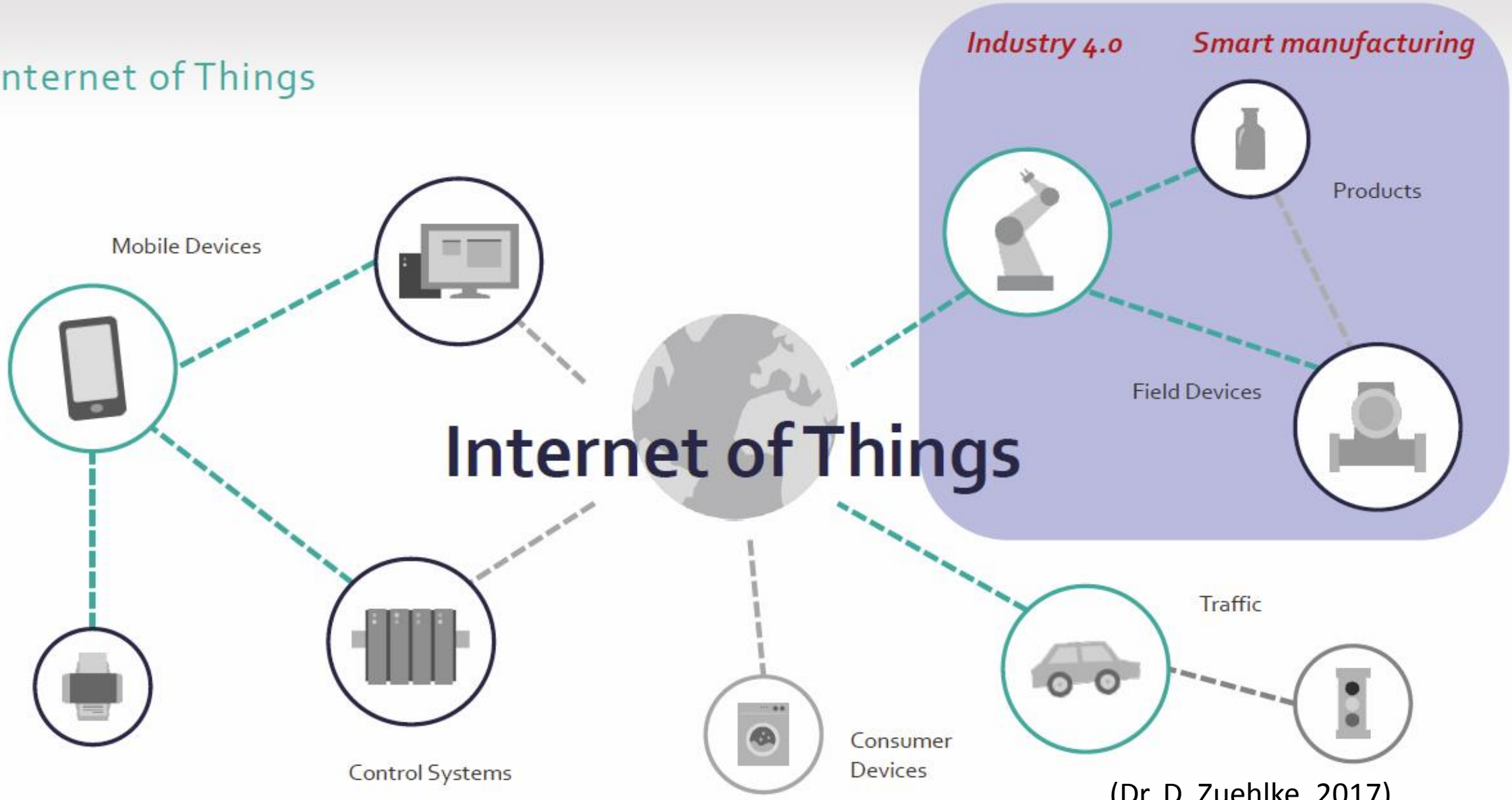
Micro-Web Servers: two kinds:

- Software: e.g. TinyWeb by Ritlabs
- Hardware:

Turning a device into a connected object:



Internet of Things



(Dr. D. Zuehlke, 2017)

Semantic Level

Obj.: To read information, understand what it means and know why it was sent

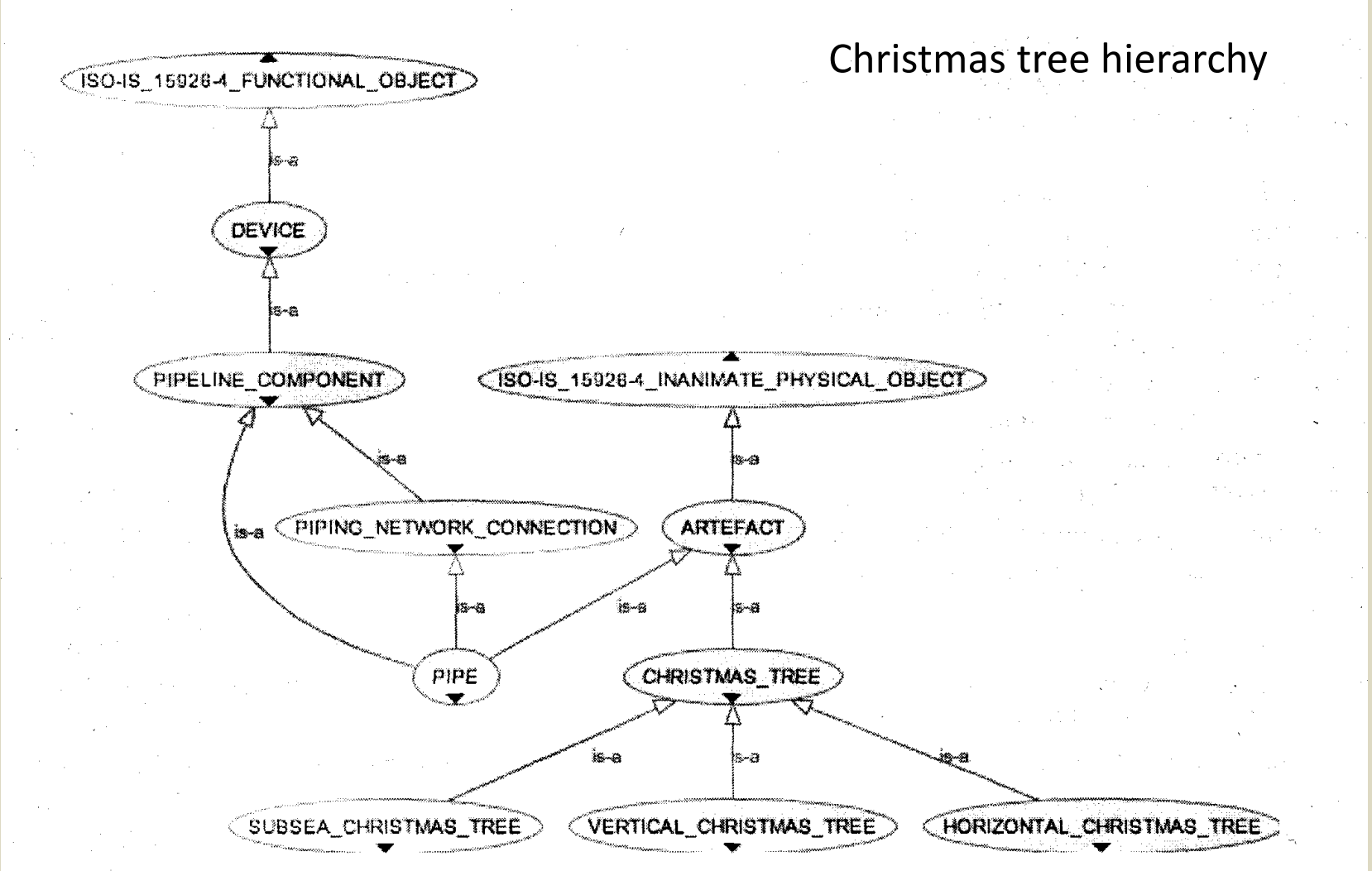
- Enterprise / Manufacturing Ontologies
- Semantic annotations
- IOF: Industrial Ontologies Foundry

Enterprise / Manufacturing Ontologies

- **Ontology:** An explicit specification of a shared conceptualization in a certain domain (Neches et al., 91 Gruber, 93)
- Idea of using ontology in EI introduced at 1st ICEIMT, 1991
- Pioneering work: The TOVE Project (M. Fox et al., Toronto Univ.)
- Then, numerous research proposals since 2000, among which
  - The Enterprise Ontology (Uschold et al., U. of Edinbourgh, 1996)
  - The Formal Manufacturing Reference Ontology + MCCO (Usman/Young/Harding/Palmer et al. , Loughborough Univ.) – See also K. Popplewell et al., Coventry Univ.

- Ontology representations:
  - Drafting: UML object classes
  - Formal specification: Semantic networks
  - Formal languages: CL (ISO/IEC 24707), RDF/OWL DL, KFL…

Ontology example in petroleum industry



F.B. Vernadat

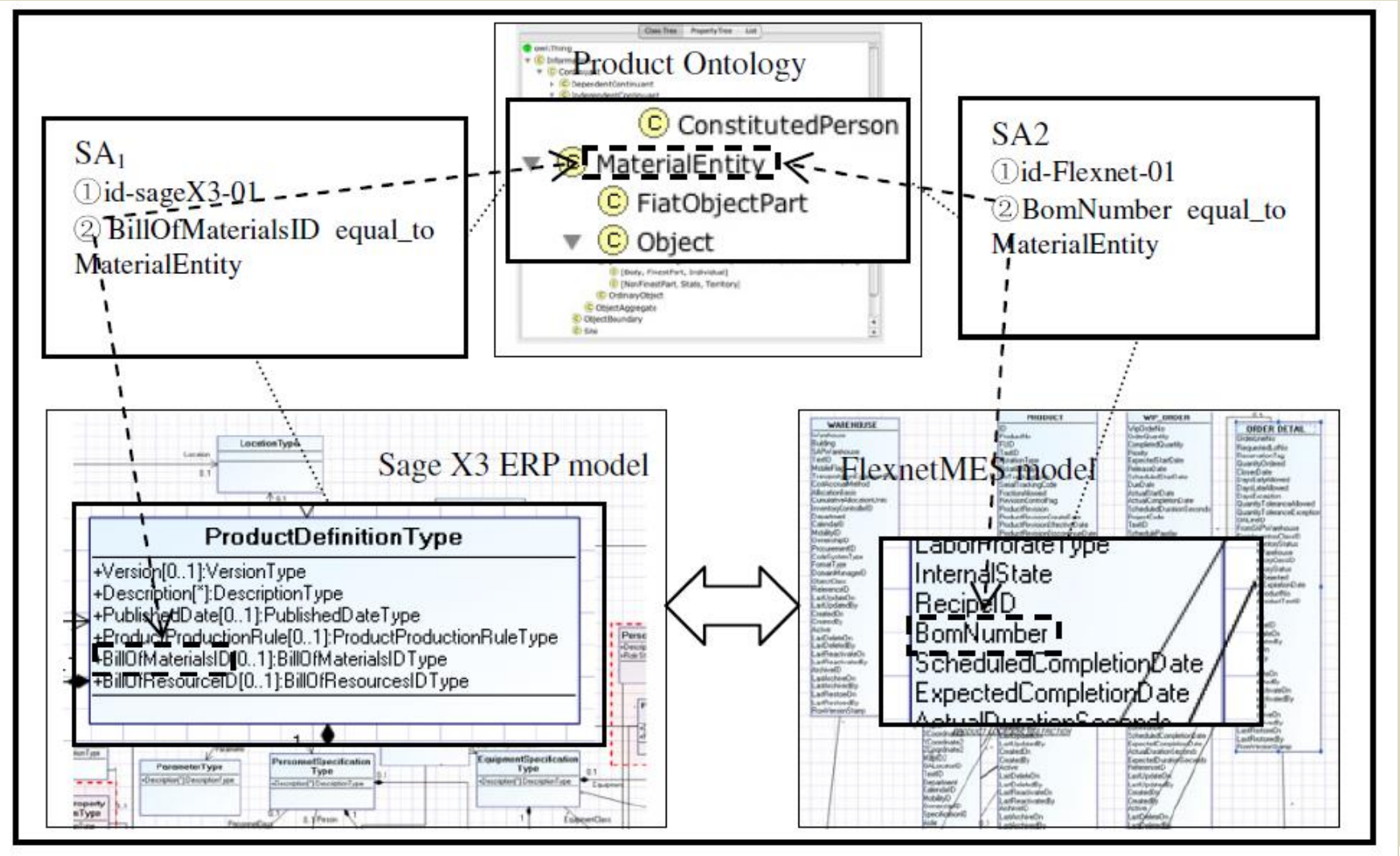
Christmas tree hierarchy in RDF/OWL

```
<owl:Class rdf:about="#CHRISTMAS_TREE">
    …
    <dc:description
    rdf:datatype="http://www.w3.org/2001/XMLSchema#string">
            An artefact that is an assembly of pipes and piping parts, with
            valves and associated control equipment that is connected to the
            top of a wellhead and is intended for control of fluid from a well.
    </dc:description>
    <dc:title
     rdf:datatype="http://www.w3.org/2001/XMLSchema#string">
            CHRISTMAS_TREE
    </dc:title>
    …
    <rdfs:subClassOf rdf:resource="#ARTEFACT"/>
</owl:Class>
```

Semantic Annotations

- **Semantic annotation:** a kind of formal (machine and human readable) metadata
- The process of tagging documents with relevant concepts, described in a knowledge graph (preferably, an ontology)
- **IT definition**: Action and result of describing an electronic resource by means of metadata whose meaning is formally specified in an ontology (Fernandez, 2010)
- **Purpose:** Added information can be interpreted (depending on context and objective) to address the gap between different data/model structures

Semantic Annotations: Example



S. Liao / Lezoche / Panetto et al., 2011

IOF

- **Industrial Ontologies Foundry:** a group working to
  - co-create a set of open ontologies to support needs of the manufacturing and engineering industry and
  - advance data interoperability

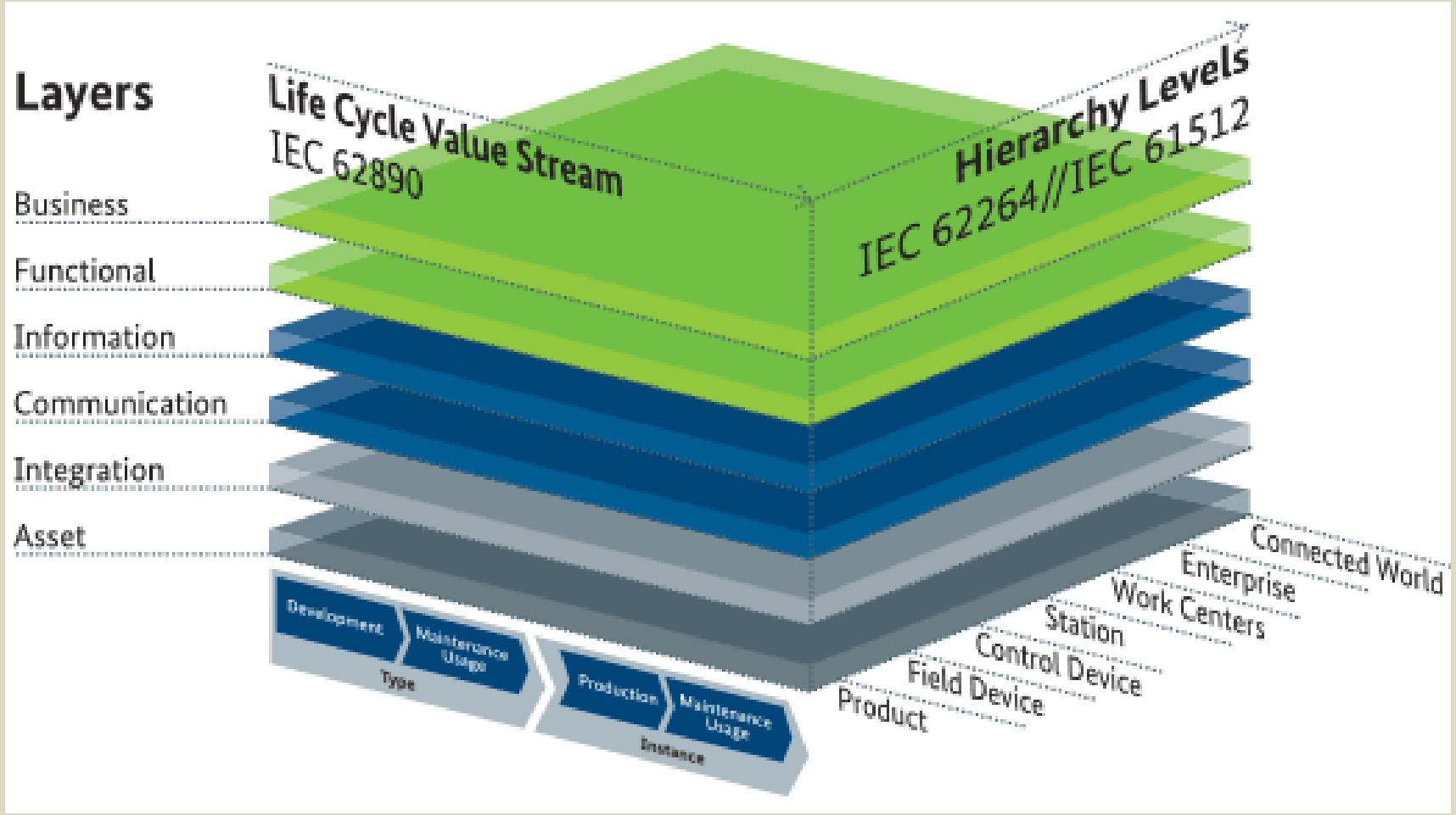
- On-going reference ontologies in domain areas such as
  - production planning and scheduling
  - supply chains
  - maintenance
  - product-service systems

Organizational Level

Obj.: To work together and jointly solve problems

- Enterprise Interoperability Frameworks (EIFs)
  - FEI, EIF, FIF…
- RAMI 4.0 by ISA
- 5C Architecture (for CPS implementation)

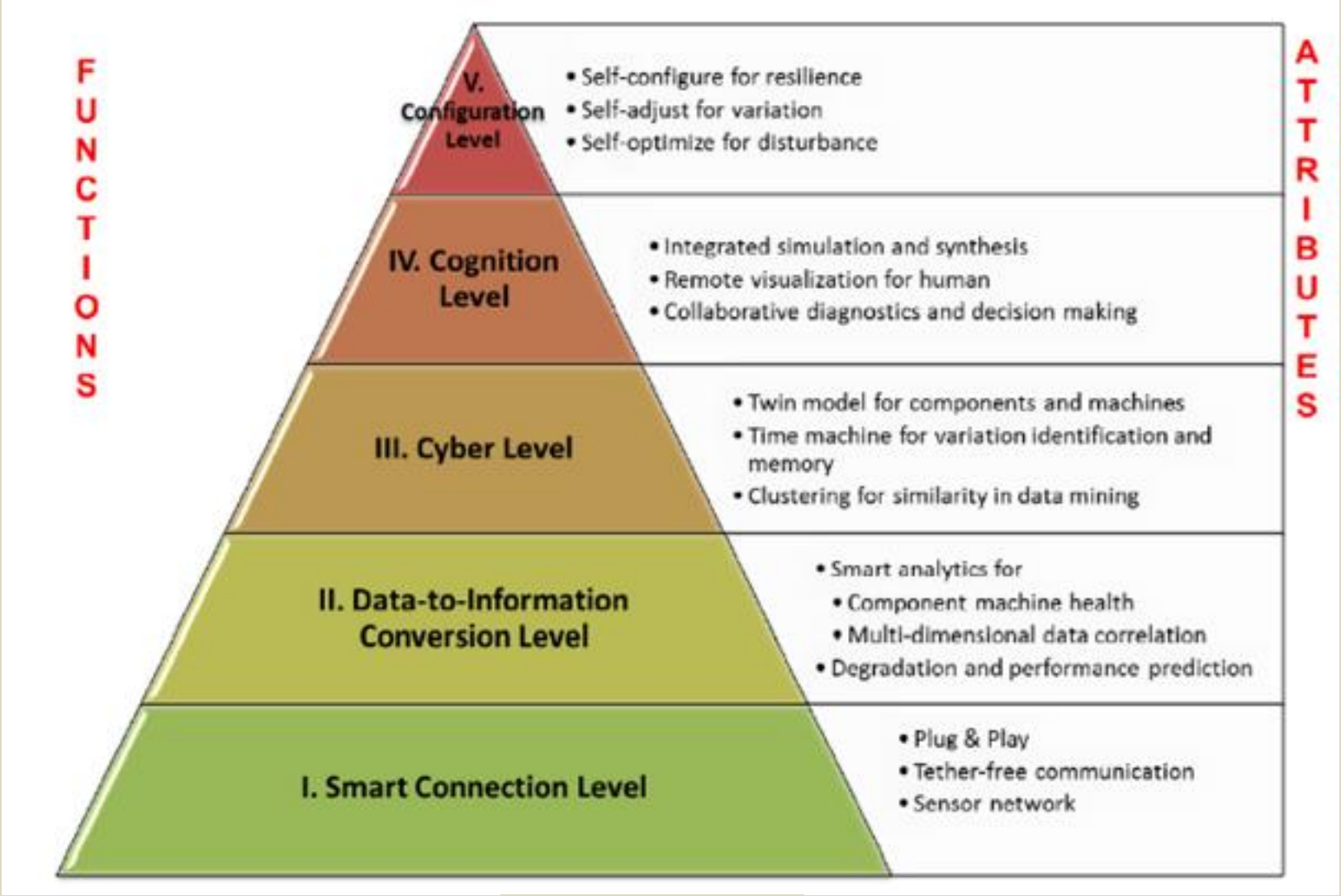
RAMI 4.0 ISA



Reference Architecture Model for Industry 4.0

F.B. Vernadat

5C Architecture for CPS Implementation



(Lee et al., 2015)

Conclusion

- Technical Level
  - Proven, efficient and robust solutions available
  - Further progress depends on ICT technical advances. Main issues: cyber-security, data integrity and system reliability
- Organization Level
  - Well understood and mastered
  - Main issues: Legal issues, especially at international levels, and trust mgt
- Semantic Level
  - Academic solutions only. Few wide-range or heavy-duty applications in industry
  - Main issues: Ontology completeness & agreement. Multilingualism

Final words for young researchers

- Industry 4.0, 5.0, …, n.0
  - Distributed decision-making & pb solving
  - Increased machine intelligence & autonomy
  - Augmented operators
  - Wonderful, but: Role distribution? Degree of autonomy? Responsibility?
- Ethical issues
  - Code of ethics (for humans, for smart machines, within CPS)
  - Transhumanism: OK, but how far? Who will set the borderlines?

IFAC
INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL

INCOM 2021 BUDAPEST

Thank you for your attention

If I could only think as fast as a computer and process big data!

If I could only dream and have emotions like Humans do!

vernadat30@gmail.com

F.B. Vernadat

lgipm Laboratoire de Génie Industriel, de Production et de Maintenance

UNIVERSITÉ DE LORRAINE