Principles and Practices of Systems Engineering

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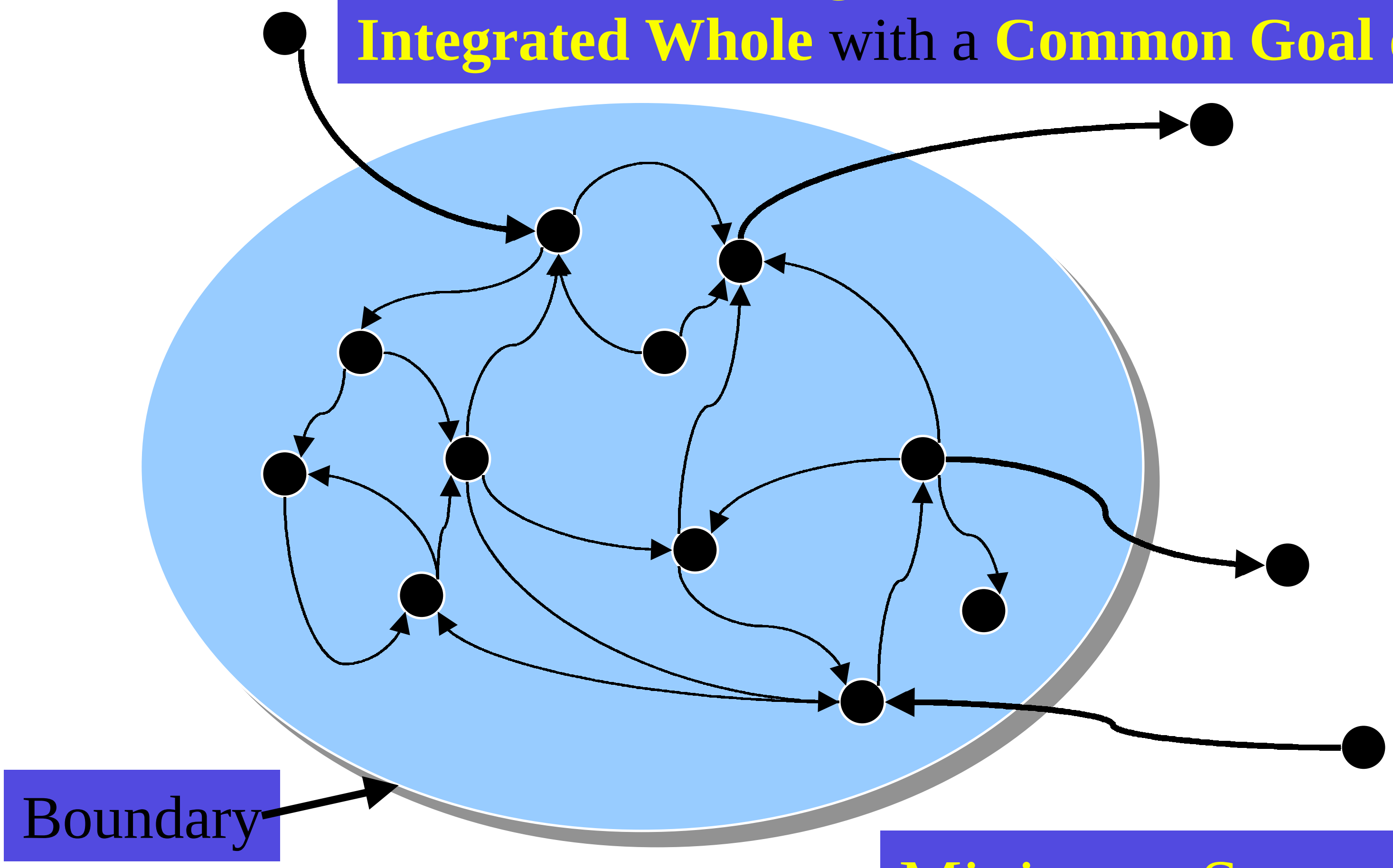
What is Systems Engineering

* Systems Thinking
  > System exists throughout the natural and man-made world, wherever we have complex behaviour "emerging" from the interaction between things.
  > We can only fully understand such behaviour by considering "complete systems" as they interact within their "natural" environment.
* To solve complex "System Problems" we must engineer complete "System Solutions", through a combination of:
  > The ability to understand, describe, predict, specify and measure the ways in which elements of a complex system affect whole system behaviour.
  > The ability to apply "Traditional" engineering knowledge to create, modify or use system elements to manipulate or maintain whole system behaviour.
  > The ability to organise, manage and resource projects in such a way as to achieve the above aims, within realistic constraints of cost, time and risk.

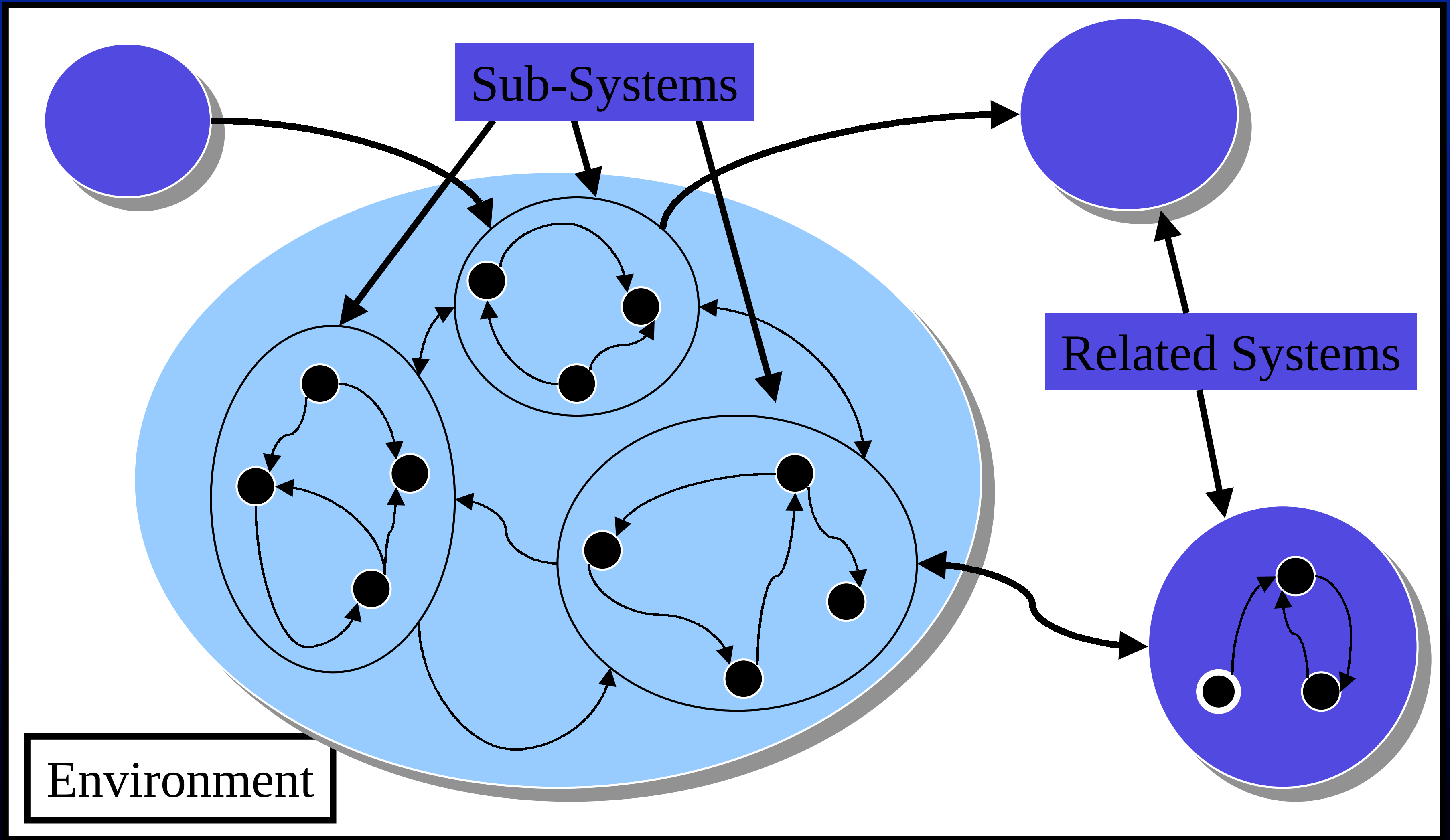
What is ‘the System’ ?

A set of **Interacting Elements** that form an **Integrated Whole** with a **Common Goal or Purpose.**



Minimum System Definition

What is 'the System' ?



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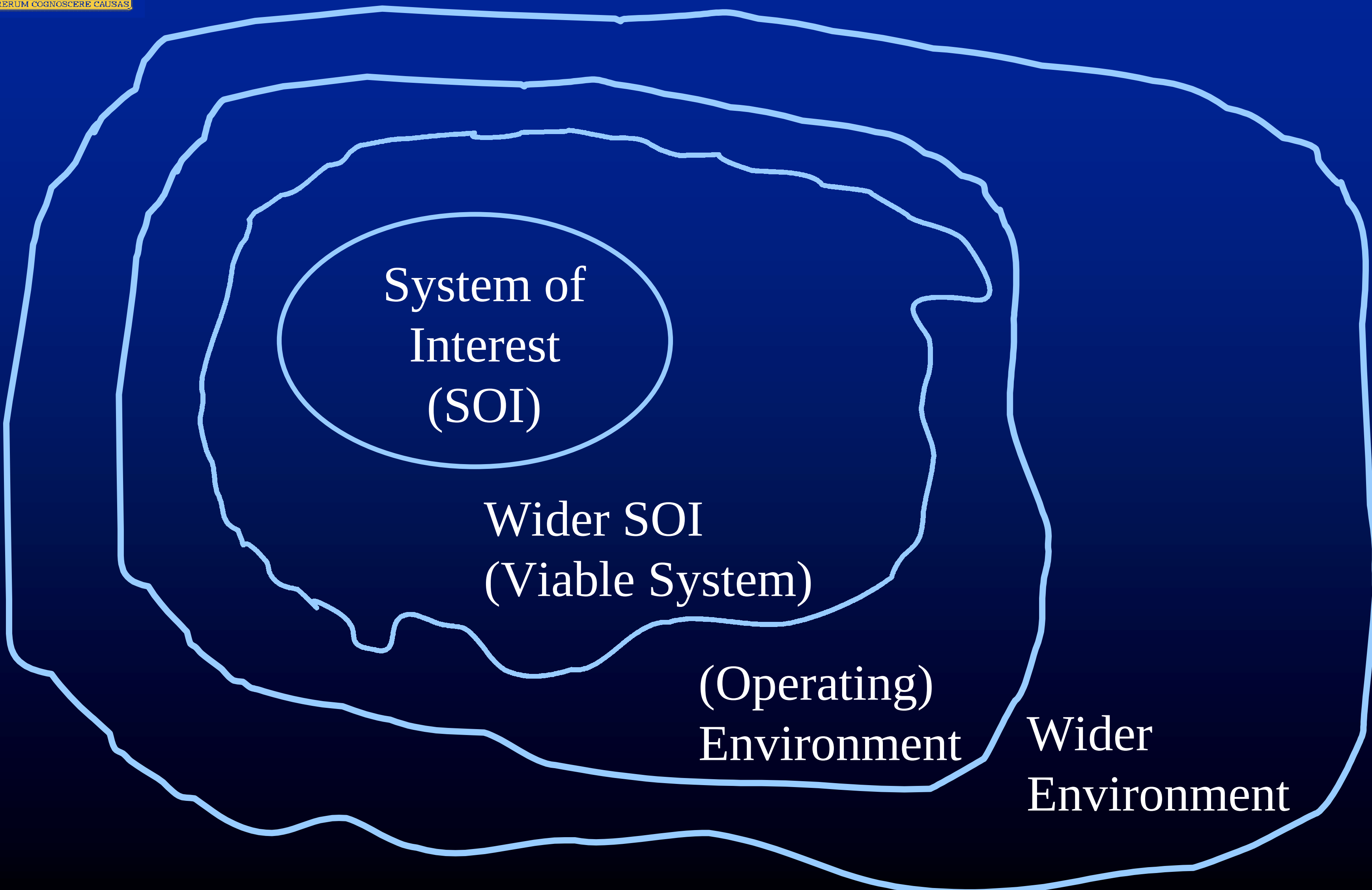
Holism and Emergence

- Holism:
  - considers the Whole-System, in its environment, through its Whole-Life
  - System of Interest, collection of elements with a common identify, e.g. product, organization.
  - Viable system, must include everything needed to maintain its existence and achieve its goals.
- Consequences of Holism:
  - The viability of a product generally relies upon interactions outside of its immediate (product) boundary.
  - Systems are engineered within the context of one or more “containing systems”.

System and Environment



Holism and Emergence

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* Emergence:
  > the whole entity exhibits a property which is meaningful only when attributed to the whole and NOT to one of its parts
  > Emergent properties also vary with environment and relationships to related systems.
* Consequences of Emergence
  > no guarantee of benefit from optimising parts of the system, or even all of the components independently
  > Changing the elements or interactions within a system may effect its properties, this can cause emergent properties to change at a number of system levels.

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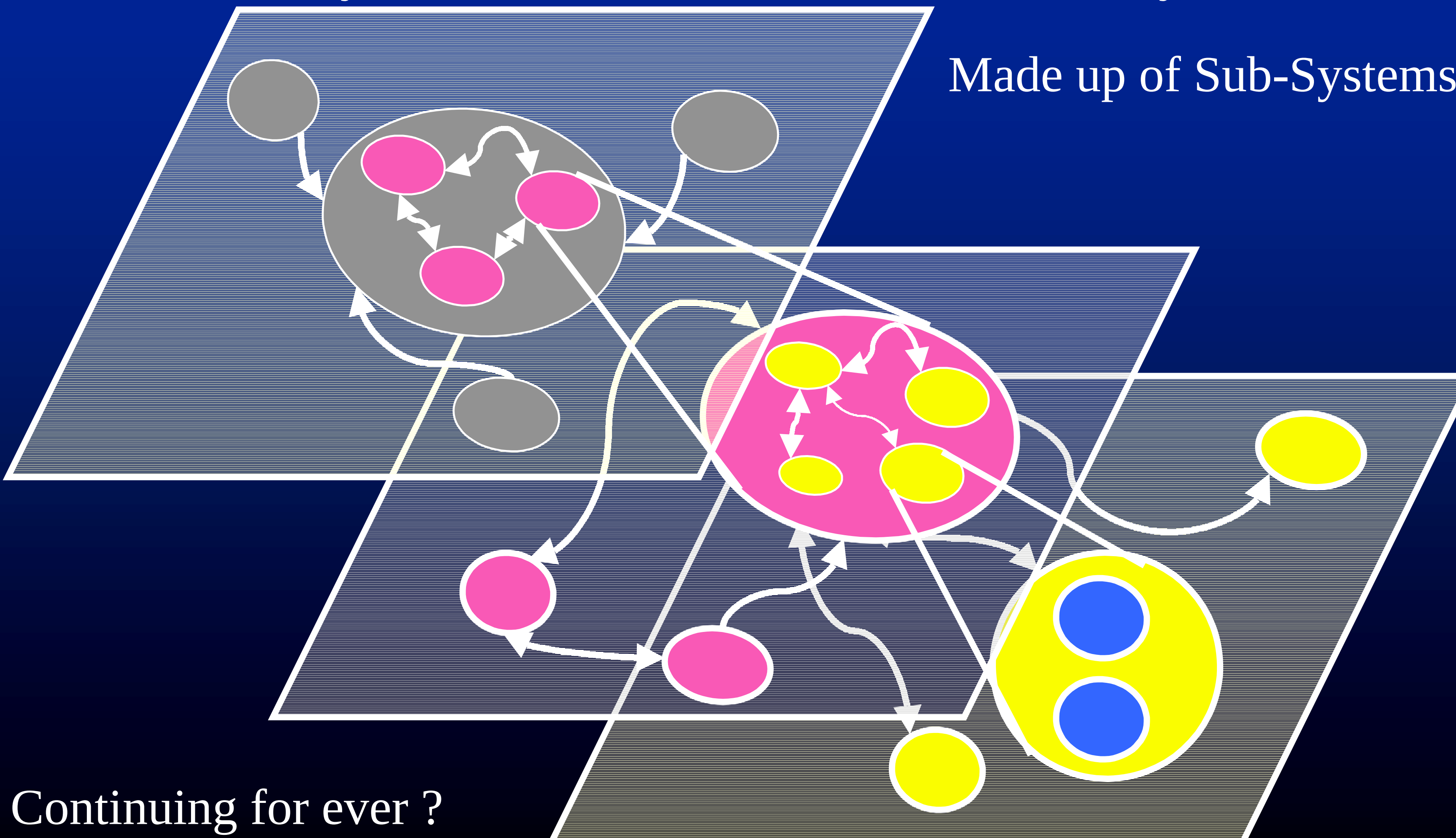
Levels of Resolution

A System, in its environment, with related Systems

Made up of Sub-Systems



Continuing for ever ?

Influences on Behaviour

* Behaviour
  > Describes the Dynamic Interactions among systems in their environment.
  > Behaviour varies with Scenario and Environment.
  > May be Goal Seeking or Reactive
* State
  > Describes the current Health, or Potential of the system.
  > May be described using State Variables, or Finite State models.
  > Establish or sustain system existence; Stability and Dynamic Equilibrium.
  > Balance between Entropy and Homeostasis

Influences on Behaviour

* Function and Structure
  > Function, task or activity; transformation of Inputs to Outputs; Static or Dynamic.
  > Structure, organisation of relationships between elements; allowable or potential behaviour.
  > Flexible, highly Adaptive vs. Specialised, efficient and highly Stable.
* Control
  > Mechanisms for Directing or Regulating function and behaviour.
  > May be Directed or Self Organising.

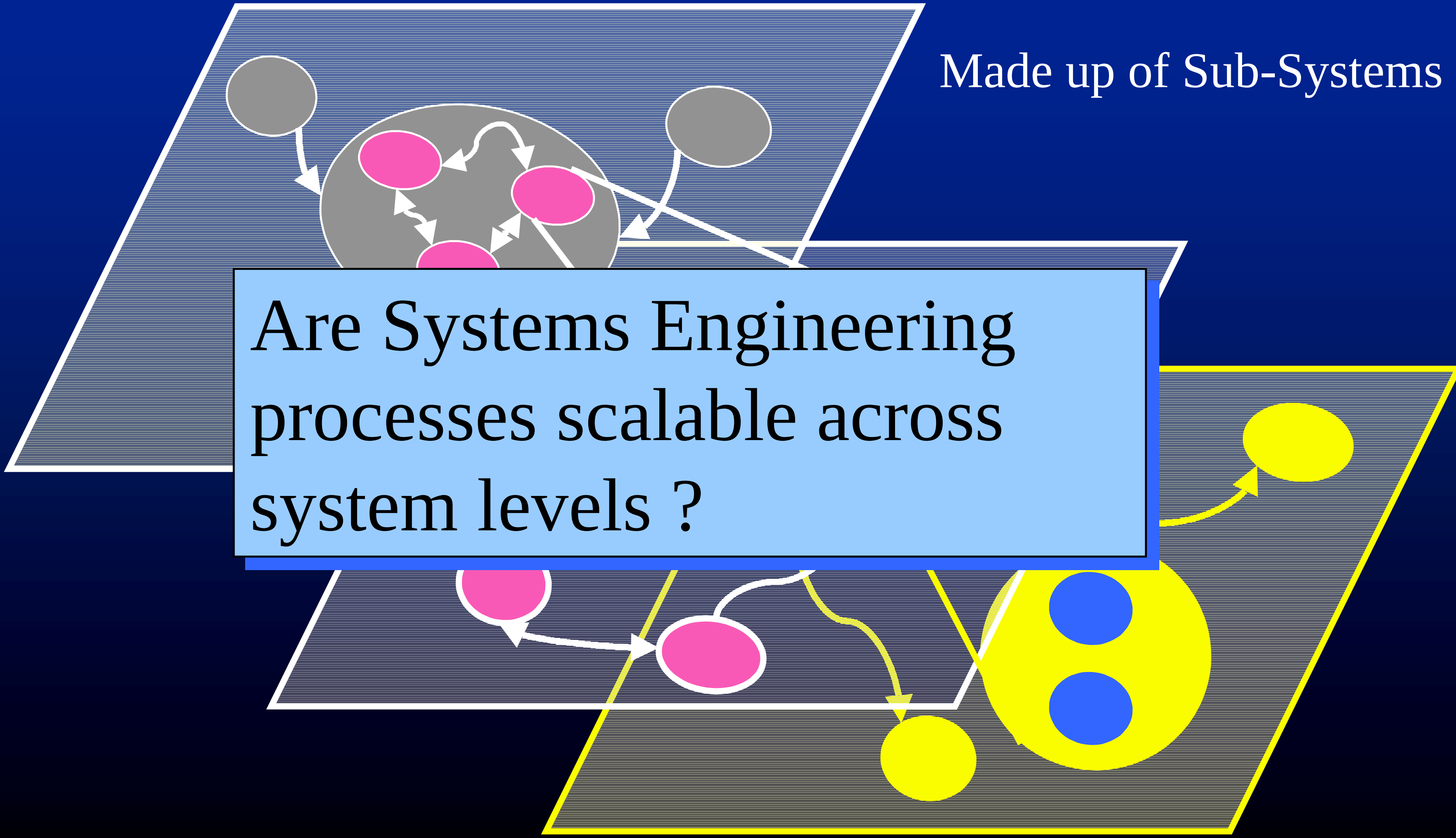
Conclusions

* Changes to the behaviour of, or relationships among, sub-system will Emerge as System Behaviour.
* In many application domains these concept are “Built-in” to organisation structures, product architectures and processes.
* This may not be sufficient for a rapidly changing, highly competitive, complex environment.
* Thus, we need to apply System Thinking directly in the development of our organisations, processes, products, etc.

Levels of Resolution

A System, in its environment, with related Systems

Made up of Sub-Systems



Are Systems Engineering processes scalable across system levels ?

Sub-Systems

* Complex interacting elements with a defined function within a system context.
* Principles of Sub-system design
  > Function/behaviour defined by transformation of input to output.
  > Highly organised, specialised structure and control.
  > Finite stable states, “predictable” exceptions and failure modes.
  > Predictable response to scenario and environment, but inflexible to unexpected change.
  > Changes to Emergent Properties impact directly on Containing System behaviour.
* Examples:
  > Computer hardware and software
  > Engine, chassis, seats and controls
  > Training, tools, test equipment, operator.
* Not all of these principles apply to sub-system design all of the time!

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Systems

* Abstract model of interacting Sub-Systems forming a Viable whole able to achieve identified mission.
* Principles of System Design
  - System mission or goal defined for identified scenarios.
  - Organised structures of closely related sub-systems (or products), may include
    - explicit control functions, or meta-system.
    - Specialist sustainment sub-systems
  - Some variety and flexibility may be built-in, through modes of operation, configuration, etc.
  - May be able to evolve to deal with changing environment or changes in use, given sufficient time and resource.
* Examples
  - Transport system, communications system
  - Integrated Military platforms, including support, training, etc.
  - Human activity systems, integrated teams, etc.

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Systems of Systems

* Abstract model of co-operating, independent Systems which may be used to provide a required capability.
* Principle of Systems of Systems "Design"
  > Loosely organised structures of cooperating systems. Highly flexible dynamic response to environment, a high degree of Equifinity.
  > "Controlled" by rules of interaction between system, plus possible strategic control. Behaviour largely self organised, goal-seeking and adaptive
  > Types of independence:
    - Operational, able to pursue own goals or survival
    - Managerial, own development organisation and timescale.
    - Temporal, may not be aware of role in capability
  > High potential for Entropy and subsequent need for high levels of Homeostasis to maintain a Dynamically stable, non-deterministic state.
* Examples
  > Internet, battle-field, conference.

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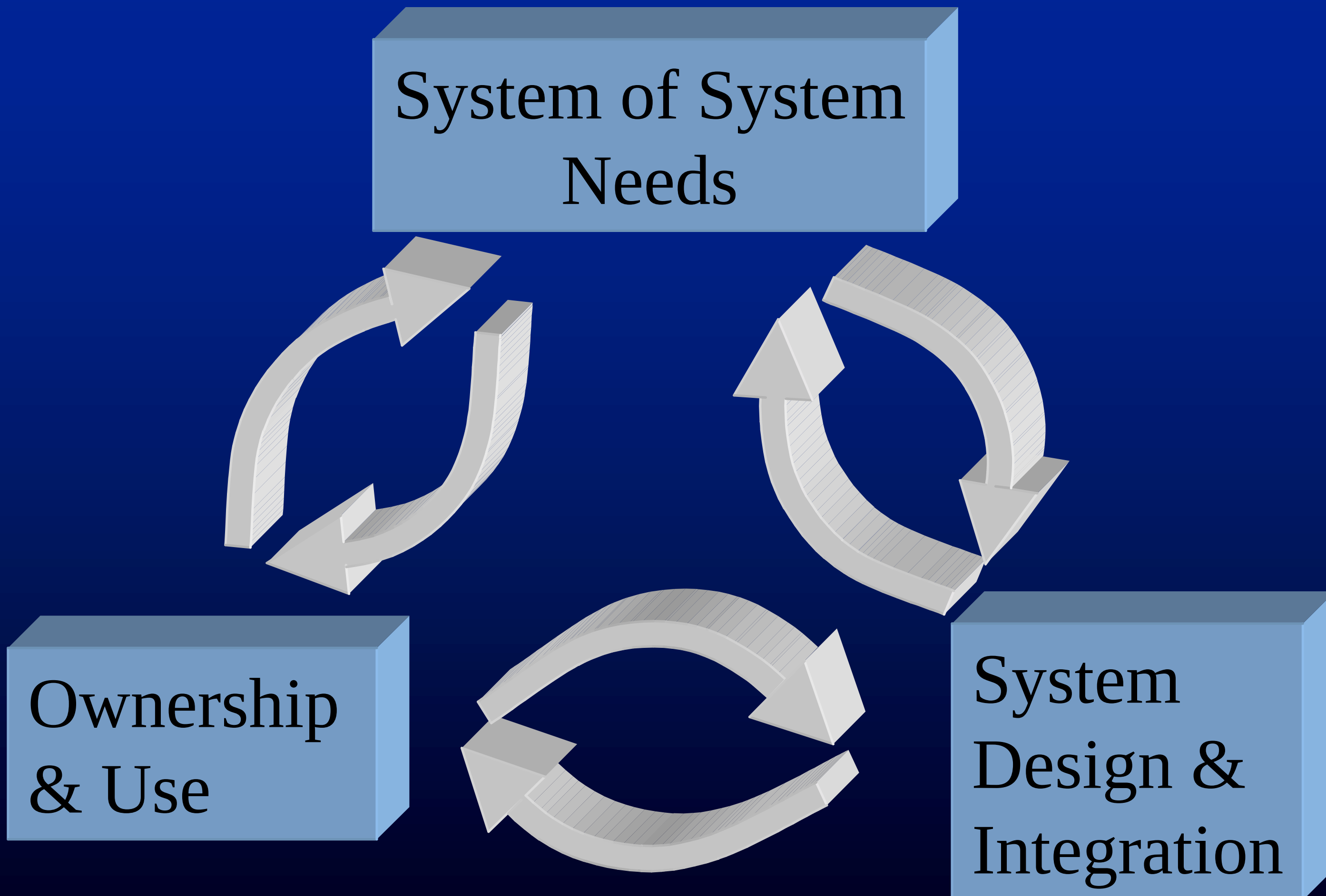
Conclusions

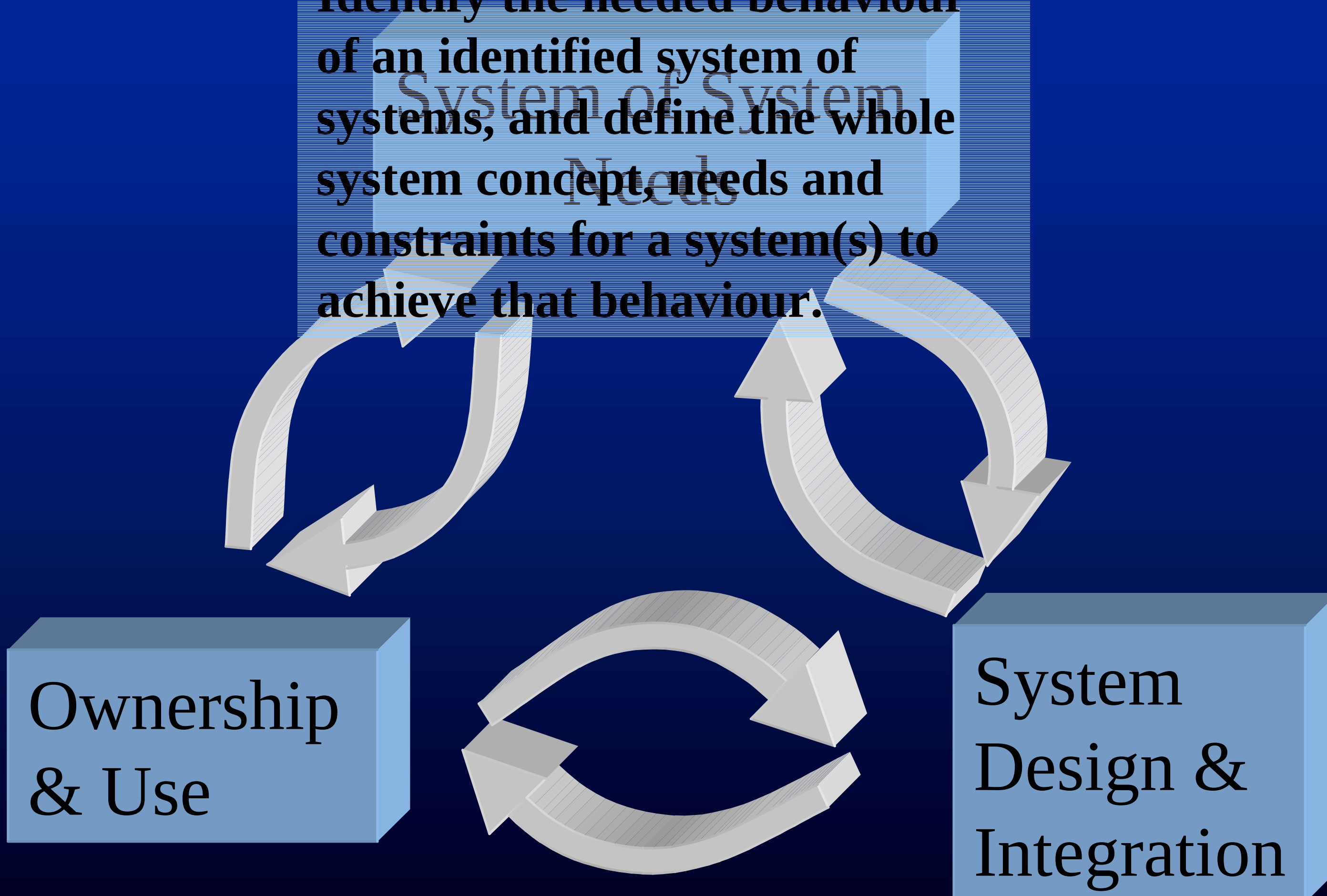
* All products are created to achieve viable whole system behaviour, and operate as part of System of Systems in the real world.
* To turn System Thinking into Systems Engineering we need:
  > Fundamental Systems principles.
  > Levels of system with different engineering needs.
  > Engineering Processes and Design Principles tailored to those needs.
* Three generic system levels exist:
  > System of Systems, views of system context and use
  > System, abstract view of viable whole system behaviour
  > Sub-system, link to real products and other engineering domains.

Three Types of Systems Engineering



Three Types of Systems Engineering

Identify the needed behaviour of an identified system of systems, and define the whole system concept, needs and constraints for a system(s) to achieve that behaviour.



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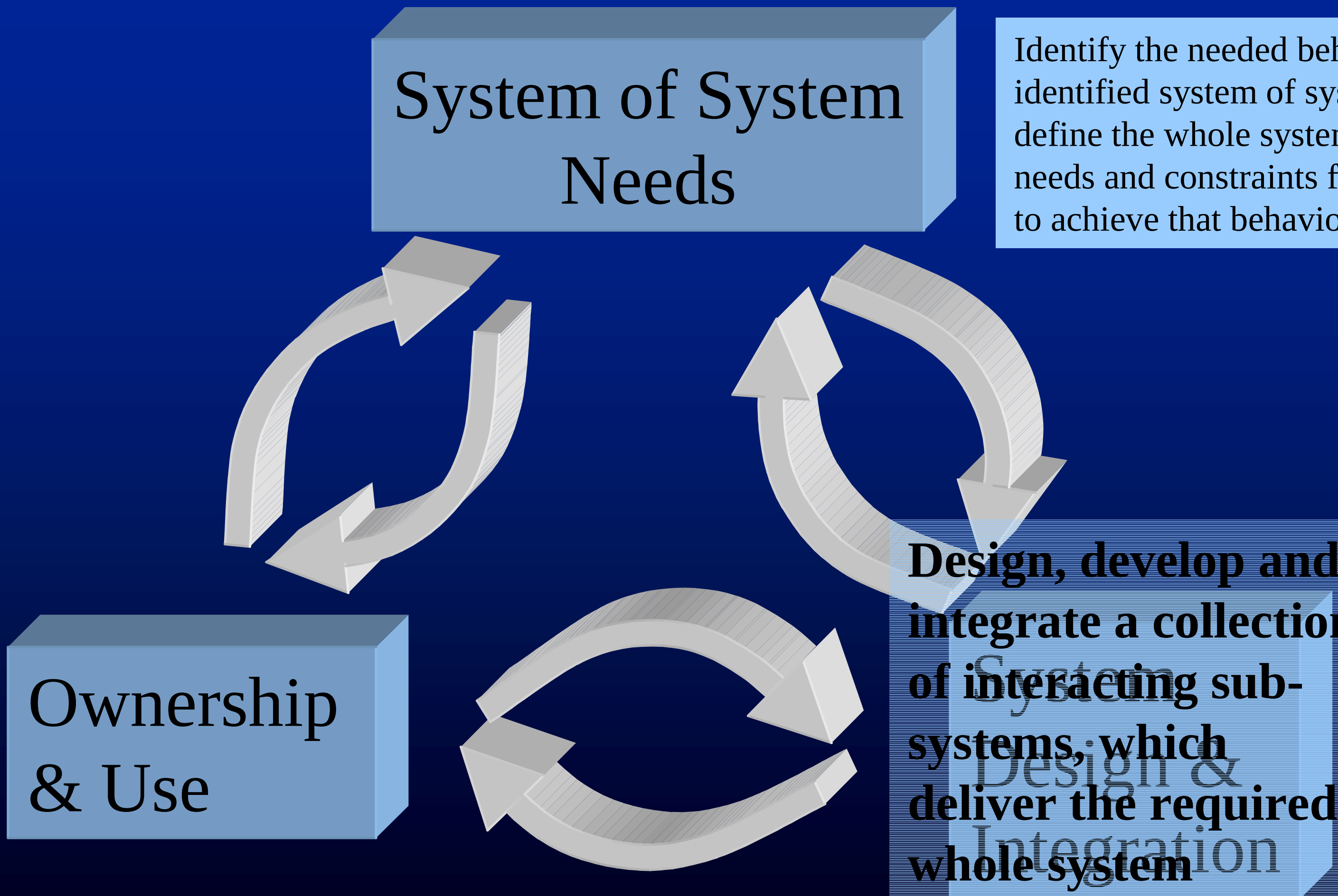
Three Types of Systems Engineering



Identify the needed behaviour of an identified system of systems, and define the whole system concept, needs and constraints for a system(s) to achieve that behaviour.

Design, develop and integrate a collection of interacting sub-systems, which deliver the required whole system behaviour

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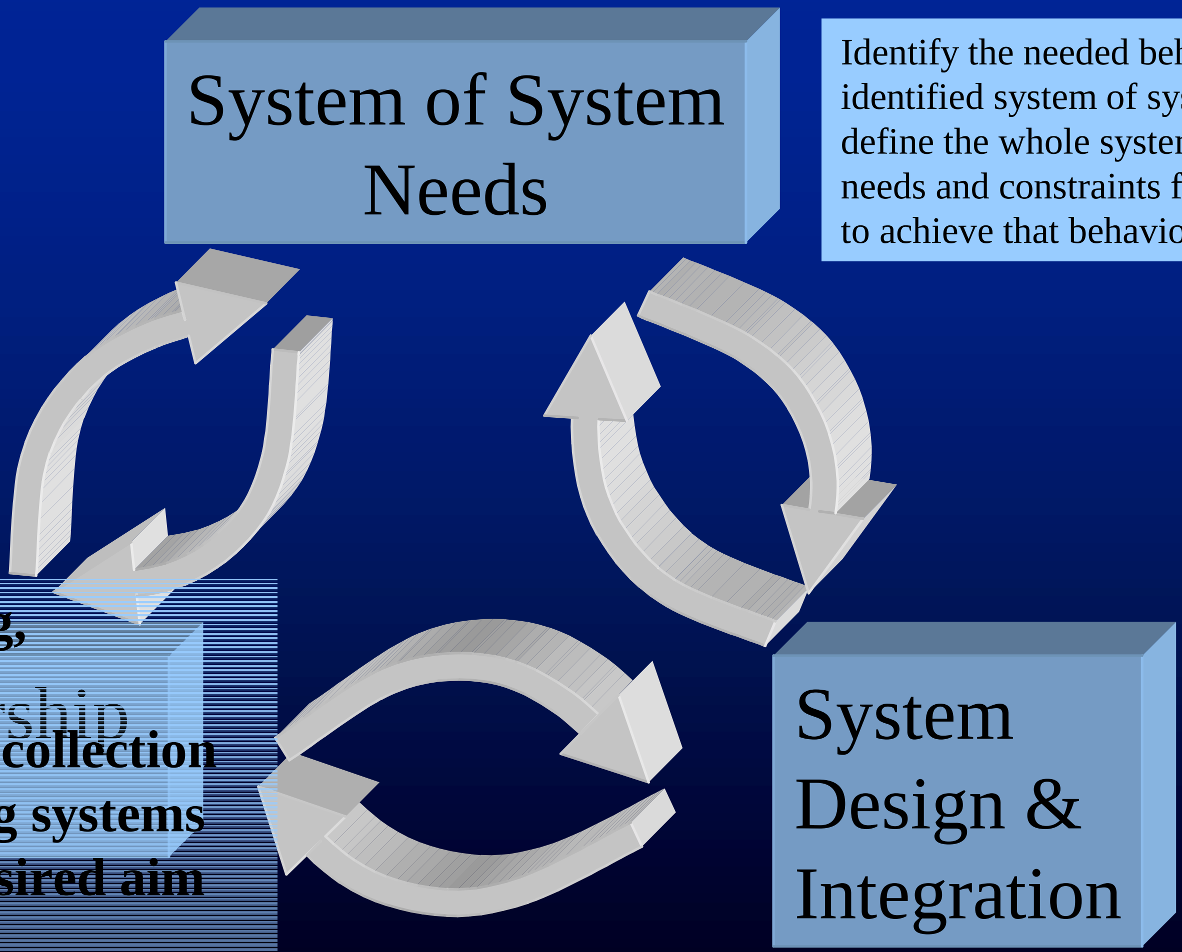
Three Types of Systems Engineering



Identify the needed behaviour of an identified system of systems, and define the whole system concept, needs and constraints for a system(s) to achieve that behaviour.

Understanding, operating and maintaining a collection of co-operating systems to deliver a desired aim or objective.

Design, develop and integrate a collection of interacting sub-systems, which deliver the required whole system behaviour

Three Types of Systems Engineering

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System of System Needs

Identify the needed behaviour of an identified system of systems, and define the whole system concept, needs and constraints for a system(s) to achieve that behaviour.

Ownership & Use

Understanding, operating and maintaining a collection of co-operating systems to deliver a desired aim or objective.

System Design & Integration

Design, develop and integrate a collection of interacting sub-systems, which deliver the required whole system behaviour

System of System Needs Challenges

* **Complexity**
  > Uncertainty of problem, interactions with other capabilities
  > Flexibility, numbers of possible system interactions
  > Emergent behaviours, Chaos effect
  > Asynchronous relationships, Human subjectivity
* **Other issues**
  > Commercial and political factors
  > Technology strategy
* **Systems Engineering skills**
  > Soft systems understanding
  > Understanding/modelling System of Systems
  > Multi-stakeholder viewpoints, and multi-discipline teams
  > System concept development and selection
  > Requirements capture/engineering

Architectural Design & Integration Challenges

* **Complexity**
  > Capability driven solution concepts
  > Viable whole system constraints
  > Sub-system optimisation and emergence
  > Highly integrated product architectures
* **Technical issues**
  > Technology push, rapid pace of sub-system development
  > COTS
* **Other issues**
  > Reduced lifecycle and market
  > Push for constant improvement
* **Systems Engineering skills**
  > Architectural design
  > Incremental & Simulation based acquisition
  > Integrated Supply chain management

Systems of Systems Ownership and Use - Challenges

- **Strategic vision**
  - Speed of change
  - potential for integration
  - Political expedience
- **Threats**
  - High initial costs
  - Globalisation
  - Protected and niche markets
- **Systems Engineering skills**
  - Strategic system approach
  - Multi-stakeholder viewpoints, and multi-discipline teams
  - Understanding/modelling System of Systems
  - Strong link into system concepts definition

Conclusions

* Three types of Systems Engineering exist to deal with:
  > Understanding real world system of system problems ….
  > …. design, and development of system products …
  > …. ownership and use of system solutions.
* These require a range of skills:
  > Covering both Hard and Soft analysis and design methods.
  > Across all Stakeholders e.g. customers, researchers, developers, evaluators, owners, operators, maintainers, etc.
  > Across a range of disciplines e.g. management, IT, simulation, analysis, design, manufacture, safety, etc.
  > Based around a set of Common System Principles e.g. Boundary, Holism, Emergence, Behaviour, State, Function, Control, Viability, etc.

Summary

* Principles
  > Need for Systems Thinking at all levels
  > Three distinct levels of System Thinking
* Practices
  > Three domains of Systems Engineering, covering Problem, Development and Ownership.
  > Consequential need for:
    - Common principles, vision and understanding
    - Wide range of Processes, Methods and tools
    - Cross discipline and stakeholders application