THE STATE OF GRADUATE SYSTEMS ENGINEERING EDUCATION IN THE US

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AGENDA

- Purpose
- My background
- INCOSE Education Initiatives
- Systems Engineering Jobs
- Graduate Programs as a System
- Considerations in the Development of a Systems Engineering Program
- Graduate SE Programs in the US
- INCOSE's Graduate Reference Curriculum For Systems Engineering (GRCSE)
- Systems Engineering Graduate Curricula
- Summary
- References

PURPOSE

- The purpose of this presentation is to provide an overview of:
  - INCOSE's current education-related initiatives
  - The state of Graduate SE Education in the US
  - Considerations associated with developing and maintain a graduate systems engineering program
  - The content of typical graduate systems engineering programs

MY BACKGROUND

- Education:
  - B.A. in Physics from Carleton College
  - Ph.D. in Physics from the University of Notre Dame (Biophysics and Biochemistry)
  - M.S. in Systems Engineering from George Mason University
- Professional Experience:
  - Systems Engineering Leadership experience at TRW/Northrup Grumman (20+ years)
    - Systems Engineering Department Manager
    - Deputy Director of TRW's Center for Advanced Technology
    - Manager of Proposal Operations
    - Lead Systems Engineer/System Architect
  - Research Associate at Institute for Defense Analyses (4 years)
- Academic Experience:
  - Assistant Professor of Physics at Muhlenberg College (5 years)
  - Adjunct Professor of Telecommunications at UM-University College (2 years)
  - Adjunct Professor in SE at UM-Baltimore County (8 years)
  - Director SE Programs at UM-College Park (5+ years)

SE ENVIRONMENT: ENGINEERING SALARY & JOBS (2019)

- **Mean Salaries in $K (from indeed.com, 9/11/19):**

Mean SE Salaries in $K (from indeed.com	9/11/19			
Type of Engineer	**Mean**	**Entry**	**Junior**	**Senior**
Software Engineer	$ 105.9			$ 122.6
System Engineer	**$ 105.5**		**$ 60.0**	**$ 111.5**
Reliability Engineer	$ 101.4			$ 106.1
Chemical Engineer	$ 93.4		$ 65.7	$ 101.0
Materials Engineer	$ 89.0			
Electrical Engineer	$ 85.5	$ 57.6		$ 105.8
Mechanical Engineer	$ 81.4	$ 57.2	$ 65.6	$ 95.6
Civil Engineer	$ 80.6	$ 55.9	$ 65.0	$ 93.1
Aeronautical Engineer	$ 77.7			
Biomedical Engineer	$ 75.9			
Industrial Engineer	$ 73.7			$ 79.9
Engineering Project Manager	$ 94.3			
Project Manager	$ 79.9			$ 101.1
Program Manager	$ 70.0			$ 102.5

- **New Jobs Posted (from indeed.com, 9/11/19):**

New Jobs (indeed.com)	9/11/19		
Type of Engineer	**MD**	VA	US
Software Engineer	2,300	3,500	52,600
System Engineer	**2,000**	**2,800**	**41,842**
Mechanical Engineer	330	480	14,400
Materials Engineer	410	510	13,500
Electrical Engineer	420	540	13,300
Industrial Engineer	115	245	7,400
Civil Engineer	180	470	6,400
Reliability Engineer	145	200	5,400
Chemical Engineer	110	105	4,000
Aerospace Engineer	90	175	3,700
Biomedical Engineer	45	15	610

Entry/Junior (20s-30s) -> Sr (~40s+)

INCOSE EDUCATION INITIATIVES

- **Graduate Reference Curriculum for Systems Engineering (GRCSE®)**
  - Version 1.0 (2012)
  - Version 1.1 (2015)
  - **Revision process began at IS 2018**
- ABET General Engineering Criteria Approved in early 2019
- Systems Engineering ABET Criteria
  - Draft criteria submitted to ABET in July 2019.
  - IISE indicated they needed more time to review/evaluate.
  - Draft criteria revised.
- System Engineering For All Undergraduate Engineers
  - Began at IS 2018

CONSIDERATIONS WHEN DEVELOPING A GRADUATE SE PROGRAM

- A Systems Engineering Graduate Program is a System
  - Identify customer(s), other stakeholders, and stakeholder needs
  - Understand the environment (students and employers)
  - Identify existing infrastructure and constraints
    - Existing faculty expertise and interests
  - Identify relevant standards and benchmark programs
  - Determine type of systems engineering program that is required
    - Determine Core Curriculum
    - Identify Concentration Areas and Electives
    - Determine Admission Criteria
  - Validate Proposed Program
  - Implement
    - Develop Curriculum
    - Recruit Faculty
    - Recruit Students
  - Validate Implementation

SYSTEMS ENGINEERING EDUCATION AS A SYSTEM

- SE Education Domain
  - System:
    - Graduate SE Program
  - Stakeholders/Users/Environment
    - Students
    - University
      - Faculty
      - Administration
    - Industry
    - Government
    - Professional Societies
      - INCOSE
      - IISE
      - IEEE
      - SAE
      - Others

STUDENTS

- Working Students
  - Generally US Students
- Full-time Students
  - Generally fresh out of undergraduate program (no work experience)
  - ~50-80% are international students

“SYSTEMS ENGINEERING” PROGRAMS

- Types of “Systems” Graduate Programs:
  - **Systems Engineering**
  - Industrial and Systems Engineering
  - <Domain> Systems Engineering
    - Control
    - Space
    - Information
    - Transportation
    - Security
    - …
  - Engineering Systems (MIT)
  - System Science
  - Engineering Management

- Degree Levels:
  - BS
    - Major
    - Minor
  - Certificate
  - **MS or MEng**
  - PhD

OVERVIEW OF SE GRADUATE PROGRAMS

- US News and World Report:
  - https://www.usnews.com/best-graduate-schools/top-engineering-schools/industrial-engineering-rankings
  - Lumps together industrial, manufacturing and systems engineering programs
  - It only identifies universities that have PhD programs.
  - 2018 Rankings
    - Total: 92 (81 ranked, 11 unranked)
    - Of the top 50 Schools (from IWWD)
      - ~13 offer PhD in SE
      - ~17 offer MS in SE

  - INCOSE Worldwide Directory (IWWD) of SE and IE Academic Programs (2017):
    - https://www.incose.org/academic-affairs-and-careers/se-education/world-wide-programs
    - U.S Total: 127
      - SE MS: 39
      - I&SE (only) MS: 17
      - IE (only) MS: 43
      - SE PhD: 24
      - I&SE (only) PhD: 9
      - IE (only) PhD: 41

THE LOCAL “MARKET”

- Maryland:
  - University of Maryland-College Park
  - University of Maryland-Baltimore County
  - University of Maryland-University College
  - Johns Hopkins University
- DC:
  - George Washington University
  - Georgetown University
- Virginia:
  - George Mason University
  - Virginia Tech
  - University of Virginia
  - Old Dominion University

SE GRADUATE PROGRAM DEVELOPMENT GUIDELINES

- Faculty Expertise/Opinion
- Industry Advisory Boards
- Government Guidelines:
  - Defense Acquisition University (DAU) references
  - NASA references
  - …
- Industry Standards
  - **ISO/IEC/IEEE 15288**
- Professional Society Guidelines
  - **Graduate Reference Curriculum for Systems Engineering (GRCSE)**
  - **CSEP Certification**

THE SYSTEMS ENGINEER (K&S)

- Systems Engineers require a unique balance of:
  - Technical depth
  - Technical breadth, and
  - Management expertise

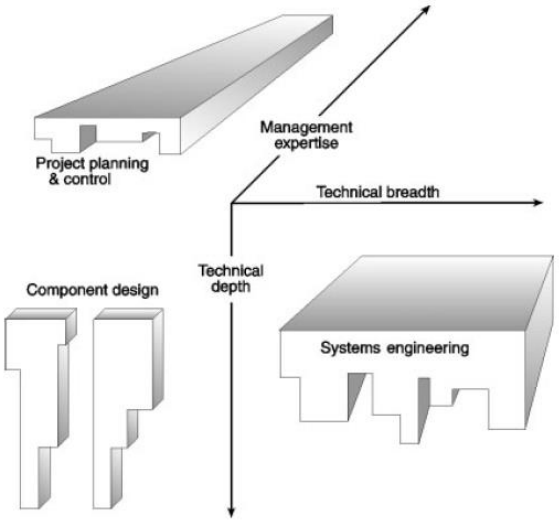


Fig. 1-3 The dimensions of design, systems engineering, and project planning and control.

- System Engineers also generally have unique blend of technical perspectives that balance:
  - Engineering
  - Mathematics, and
  - Science

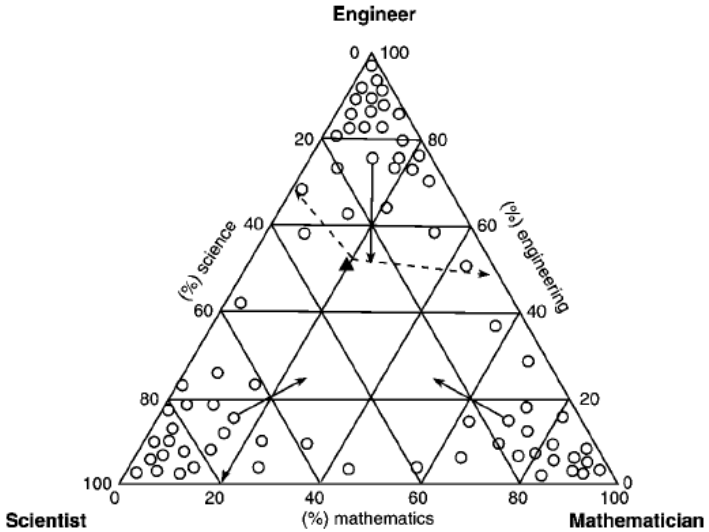


Fig. 1-4b Technical orientation population density distribution.

From Systems Engineering Principles and Practice, Alexander Kossiakoff and William Sweet, 2003.

GRADUATE REFERENCE CURRICULUM FOR SYSTEMS ENGINEERING (GRCSE)

GRCSE EXECUTIVE SUMMARY [1]

- Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE™) Project:
  - Products:
    - Graduate Reference Curriculum for Systems Engineering (GRCSE)
      - V 1.0 in 2012
      - V 1.1 in 2015
    - System Engineering Body of Knowledge (SEBoK)
      - Initial Version in 2012
      - Continually updated
  - Initial authors for the BKCASE project (starting in 2009):
    - The International Council on Systems Engineering (INCOSE),
    - The Institute of Electrical and Electronics Engineers Computer Society (IEEE CS),
    - The IEEE Systems Council,
    - The Institute of Industrial Engineers (IIE)
    - The National Defense Industrial Association (NDIA) Systems Engineering Division
  - Current Governance (as of 2013):
    - **The Systems Engineering Research Center (SERC),**
    - **The International Council on Systems Engineering (INCOSE)**
    - **The Institute of Electrical and Electronics Engineers Computer Society (IEEE CS).**

GRCSE EXECUTIVE SUMMARY [2]

- GRCSE offers guidance for systems-centric professional master's degree in SE, including:
  - A set of **student skills, knowledge, and experience assumed** by the curriculum for the entering student,
  - A set of **outcomes identifying the specific competencies** that will be possessed by a student who successfully completes a graduate program based on the curriculum.
  - A set of **objectives** aligned with those outcomes and describing the **near-term career go**als of such a graduate.
  - **Guidance on curriculum content,** including a Core Body of Knowledge (CorBoK).
  - A conceptual architecture to communicate and support implementation of the curriculum to achieve the outcomes and objectives.
  - Guidance on program implementation and assessment, and how & to balance the CoRBoK with the needs of the national or industrial domains being served.

GRCSE CURRICULUM ARCHITECTURE (CH 5)

- Preparatory Knowledge (Ch. 4)
- Foundation Knowledge (CorBoK)
- Concentration Knowledge (SE Management & System Design and Development)
- Domain-Specific Knowledge
- Program-Specific Knowledge
- Capstone Experience

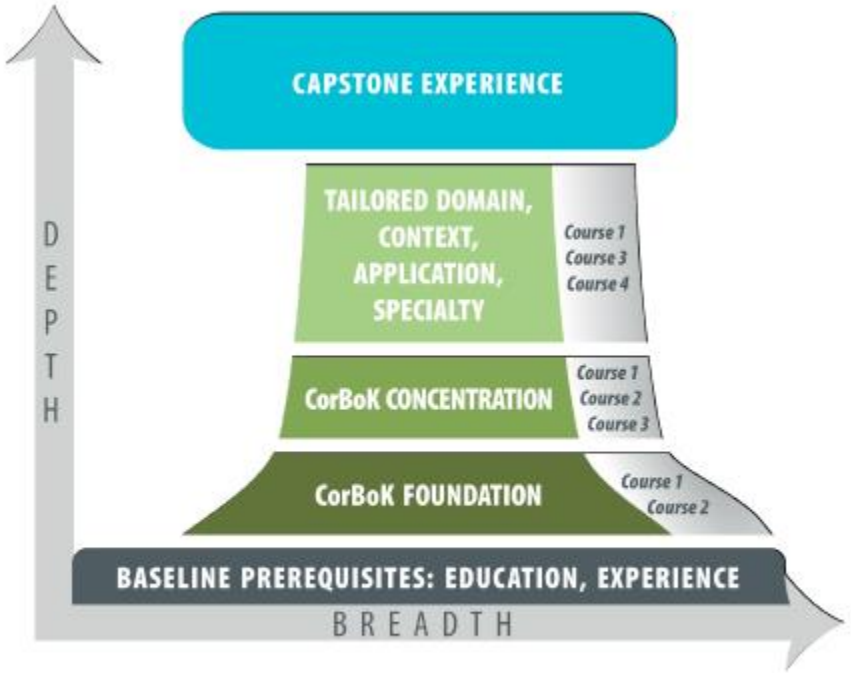


Figure 5. Course Alignment Which May Not Directly Correspond to Topics from Only One Area. (GRCSE Original)

GRCSE CORBOK (CH 6)

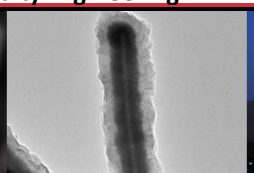
- The **CorBoK** is the body of SE knowledge that every graduate student is expected to master
  - Levels of mastery are indicated based on Bloom's Categories
- CorBoK is based on SEBoK
- **SEBoK Structure:**
  - Part 1: SEBoK Introduction
  - Part 2: Systems
  - **Part 3: SE and Management**
  - Part 4: Applications of SE
  - **Part 5: Topics on Enabling SE**
  - **Part 6: Related Disciplines**
  - Part 7: SE Implementation Examples
- **Bold => Level 2 Understanding (Application/Analysis)**

- SEBoK is consistent with INCOSE SE Handbook, Ver. 3.2.2 (2012)
- **INCOSE SE Handbook, 4th Ed. (2015) Structure:**
  1. SHE Scope
  2. Systems Engineering Overview
  3. Generic Life Cycle Stages
  4. Technical Processes
  5. Technical Management Processes
  6. Agreement Processes
  7. Organizational Project-Enabling Processes
  8. Tailoring Process
  9. Cross-Cutting SE Methods
  10. Specialty Engineering Activities

CORBOK TOPIC AREAS

Part	Area	Foundation	SEM	SDD
System Topics				
	Systems Fundamentals	Comp		
	Systems Science	Know		
	Representing Systems with Models	Know		**App**
	Systems Approach Applied to Engineering	Know		
	Systems Thinking	Know		
SE and Management				
	Life Cycle Models	**App**		
	Concept Definition	**App**		**Ann**
	System Definition	**App**		**Ann**
	System Realization	**App**		**Ann**
	System Deployment and Use	Comp		**App**
	SE Management	Comp	**Ann**	
	Product and Service Life Management	Comp	**Ann**	**App**
	SE Standards	Comp		
Applications of SE				
	Product SE	Know		
	Service SE	Know		
	Enterprise SE	Know		
	Systems of Systems	Know		
Enabling SE				
	Enabling Businesses and Enterprises	Know	Comp	
	Enabling Teams	**App**	**Ann**	
	Enabling Individuals	Comp	**App**	
Related Disciplines				
	SE and SW Engineering	Comp	**App**	**App**
	SE and PM	Comp	**App**	
	SE and Industiral Engineering	Know		
	SE and Procurement/Acquisition	Know		
	SE and Specialty Engineering	App+ for Some	App+ for Some	App+ for Some

- Table indicates Bloom level of mastery associated with each CorBoK area
  - Foundation levels are for any SE program
  - SEM and SDD levels are additional levels of mastery required for curricula that have an SEM or SDD focus
  - Items in **Bold** indicate higher levels of mastery are required.
  - Bloom's levels of mastery:
    - Knowledge (aware)
    - Comprehension (explain)
    - Application (solve)
    - Analysis (critical evaluation)




CORBOK SE & SE MANAGEMENT TOPICS [1]

Table 6. CorBoK Bloom's Levels for Part 3: SE and Management. (GRCSE Original)

Knowledge Area	Part 3 Topic	Foundation	SEM	SDD
Life Cycle Models	ife Cycle Characteristics	Application		
	System Life Cycle Process Drivers and Choices			
	System Life Cycle Process Models: Vee			
	System Life Cycle Process Models: Iterative			
	Integration of Process and Product Models			
	Lean Engineering			
Concept Definition	Mission Analysis	Application		Analysis
	Stakeholder Needs and Requirements			
System Definition	System Requirements	Application		Analysis
	Architectural Design: Logical			
	Architectural Design: Physical			
	System Analysis			
System Realization	System Implementation	Application		Analysis
	System Integration			
	System Verification			
	System Validation			

CORBOK SE & SE MANAGEMENT TOPICS [2]

Knowledge Area	Part 3 Topic	Foundation	SEM	SDD
System Deployment and Use	System Deployment	Comprehension		Application
	Operation of the System			
	System Maintenance			
	Logistics			
SE Management	Planning	Comprehension	Analysis	
	Assessment and Control			
	Risk Management			
	Measurement			
	Decision Management			
	Configuration Management			
	Information Management			
	Quality Management			
Product and Service Life Management	Service Life Extension	Comprehension	Analysis	Application
	Capability Updates, Upgrades, and Modernization			
	Disposal and Retirement			
SE Standards	Relevant Standards	Comprehension		
	Alignment and Comparison of the Standards			
	Application of SE Standards			

SYSTEMS ENGINEERING CURRICULA

TYPICAL SE CURRICULA

- SE Core:
  - SE Foundations (Concepts & Principles)
  - Requirements and Architecture
  - Analysis, Modeling, and Simulation
  - Verification and Validation
- Multiple Electives devoted to developing “depth” in a given (engineering) “domain”
- Some Common Electives:
  - Engineering/computer science courses
  - Project (Systems Engineering) Management
  - Decision and Risk Analysis
  - Quality Management Systems/Six Sigma
  - Human Factors
  - Reliability/Sustainment Engineering (RAM)
- Masters (Team) “Project” (or Thesis)

ADMISSION CRITERIA

- **Admission Criteria:**
  - BS in engineering, science, or mathematics
  - Letter(s) of recommendation
  - GPA > 3.0 (most programs)
  - Work experience (many programs)
  - GRE scores (some programs)
  - Course Work (some programs)
    - University Physics
    - **Multi-variable Calculus**
    - Probability/Statistics
    - **Differential Equations**
    - **Computer Programming Language**

GENERAL STRUCTURE

- **Curriculum (most programs):**
  - **30 Credits (10 courses)**
    - 5-6 Required (Core) Courses
    - 1 Project/Capstone Course + 3-4 Electives
    - or Master's Thesis (2 course") + 2-3 Electives
    - Electives generally in one area of concentration
  - **Core Courses:**
    - SE Concepts, Life Cycle Models, & Processes (Systems Engineering Handbook)
    - Multi-Level Requirements and Architecture
    - Design and Integration
    - Verification and Validation
    - Analysis, Modeling, and Simulation
    - Systems Engineering Management
  - **Elective/Concentration Areas:**
    - Varies widely from program to program
    - Some common areas include:
      - Human Factors
      - Decision Analysis
      - Quality Management Systems/Six Sigma
      - Network Communications
      - Software Engineering
      - Sustainment Engineering

UNIVERSITY OF MARYLAND'S PROGRAM: PROGRAM OUTCOME OBJECTIVES

#	Learning Outcomes(s)	Assessment Method(s)
1	Describe the principal systems engineering concepts, processes, methods, and activities consistent with the INCOSE Systems Engineering Handbook and ISO/IEC/IEEE 15288:2015.	Exams
2	Describe the purpose, structure, activities, and products associated with various acquisition and development life cycle models.	Exams
3	Work effectively on teams to: - Practice Model-Based Systems Engineering (MBSE) through the use of SysML to develop context-level, system-level, and element-level requirements and architecture. - Develop, verify, and validate MATLAB-based system models and simulations. - Apply various operations research-related analysis and modeling techniques to perform system performance analyses and trade-off analyses.	Class Homework, Class Projects, Exams
4	Identify and describe the basic systems engineering specialty engineering domains and why they are important.	Class Homework, Exams
5	Perform RAM analyses, risk analysis, EVM analyses, and human factors analyses.	Class Homework, Exams
5	Develop WBS-based life cycle cost estimates.	Class Homework, Class Project, Exams
6	Describe the activities that make up systems engineering management and why they are important.	Class Homework, Exams
7	Demonstrate an understanding of at least one area of specialization.	Grades for "specialization" elective courses
8	Perform systems engineering-related research.	MS Thesis or Scholarly Paper

UNIVERSITY OF MARYLAND'S PROGRAM: MASTER OF SCIENCE

- 5 Core Courses:
  - ENSE 621: Systems Engineering Concepts and Processes: A Model-Based Approach
  - ENSE 622: System Trade-off Analysis, Modeling, and Simulation
  - ENSE 623: System Development, Verification, and Validation
  - ENSE 624: Human Factors in Systems Engineering
  - ENSE 626: System Life Cycle Analysis and Risk Management
- ENSE 623 serves as "project course"

- 2 Thesis "courses" for MS
- 3 Elective Course from following areas:
  - Communications and networking systems
  - Computer and software systems
  - Control systems
  - Manufacturing systems
  - Operations research
  - Reliable systems
  - Transportation systems
  - Robotics
  - Signal processing systems
  - Cybersecurity

UNIVERSITY OF MARYLAND'S PROGRAM: MASTER OF ENGINEERING

- 5 Core Courses:
  - Same as for the MSSE
- ENS 623 serves as "project course"
- 5 Elective Courses:
  - See Certification Areas

- Certification Areas:
  - **Additive Manufacturing**
  - **Aerospace**
  - **Bioengineering**
  - **Chemical & Biomolecular**
  - **Civil & Environmental**
  - **Cybersecurity**
  - **Electrical & Computer (Computer Engineering)**
  - **Electrical & Computer (Communications & Signal Processing)**
  - **Electronic Packaging**
  - **Energy Systems Engineering**
  - **Environmental**
  - **Fire Protection (online)**
  - **Fire Protection (on campus)**
  - **Materials Science & Engineering**
  - **Mechanical (General Mechanical)**
  - **Mechanical (Energy & The Environment)**
  - **Project Management**
  - **Reliability**
  - **Robotics**
  - **Software**

JOHNS HOPKINS UNIVERSITY

- **Systems Engineering**
  - Also:
    - Space Systems Engineering
    - Systems Science & Engineering
    - Information Systems Engineering
- 6 Core Courses:
  - 662 Introduction to Systems Engineering
  - 667: Management of Systems Projects
  - 764: Software Systems Engineering
  - 767: System Conceptual Design
  - 768: System Design and Integration
  - 769: System Test and Evaluation
- 1 Project Course (or 2 Thesis “courses”)
- 3 Elective Course from following areas:
  - Systems
  - Cybersecurity
  - Human Systems
  - Modeling and Simulation
  - Project Management
  - Software Systems

STEVENS INSTITUTE OF TECHNOLOGY

- School of Systems and Enterprises
- 10 Courses
- 6 Core Courses:
  - SYS 625: Fundamentals of Systems Engineering
    - Or SYS 671: Conception of CPS: Deciding What to Build and Why
  - SYS 611: Systems Modeling & Simulation
    - or SYS 660: Decision and Risk Analysis
  - EM 612: Project Management of Complex Systems
  - Architecture and Design Course (multiple options)
  - Implementation Course (multiple options)
  - Sustainment Course (multiple options)
- 1 Project Course:
  - or Thesis (2 “courses”)
- 3 Elective Courses from following areas:
  - Systems Engineering
  - Software Engineering
  - Engineering Management
  - Socio-Technical Systems
  - System Engineering Security

VIRGINIA TECH

- Department of Industrial and Systems Engineering
  - Also Biological Systems Engineering
- 10 courses
- 3 Core Courses:
  - ENGR 5004 Systems Engineering Process
  - ENGR 5104 Applied Systems Engineering
  - ENGR 5204 Systems Engineering Project
- 3 courses in one “traditional” science or engineering discipline
- 3 courses in a second science or engineering discipline
- 1 course from outside science or engineering

GEORGE WASHINGTON UNIVERSITY

- Department of Engineering Management & Systems Engineering
- 36 credit hours (12 courses)
- 4 Core Courses:
  - EMSE 6001 The Management of Technical Organizations
  - EMSE 6410 Survey of Finance and Engineering Economics
  - EMSE 6020 Elements of Problem Solving and Decision Making for Managers
  - EMSE 6801 Systems Engineering I
- 8 Courses in one of the following “Focus Areas:”
  - Operations Research and Management Science
  - System Engineering:
    - Systems Engineering II
    - Systems Analysis and Management
    - Program and Project Management
    - Quantitative Models in Systems Engineering
    - Management of Information and Systems Security
    - Information and Software Engineering
    - Requirements Engineering
    - Special Topics

UNIVERSITY OF MINNESOTA

- Industrial & Systems Engineering
- 30 credit hours (~10 courses)
- 4 Core Courses (14 credits):
  - IE 5111. Systems Engineering I
  - IE 5113. Systems Engineering II
  - IE 5541. Project Management
  - IE 5553 Simulation
- ~6 Elective Courses (16 credits)

SUMMARY

- Presentation provided an overview of:
  - Current major INCOSE education initiatives
  - The Graduate Systems Engineering Education Environment
  - INCOSE's Graduate Reference Curriculum for Systems Engineering (GRCSE)
  - The typical structure of systems engineering programs
  - The structure & content of some typical systems engineering programs

REFERENCES

- USN&WR Best IMSE Programs: https://premium.usnews.com/best-graduate-schools/search?program=top-engineering-schools&specialty=industrial-engineering
- INCOSE Directory of Systems Engineering Academic Programs: http://www.incose.org/educationcareers/academicprogramdirectory.aspx
- Wikipedia: https://en.wikipedia.org/wiki/List_of_systems_engineering_universities
- GRCSE
  - https://www.bkcase.org/Grcse/
- University Systems Engineering Program Web Sites
  - https://isr.umd.edu/education/systems-engineering-education

QUESTIONS?


The
Institute for
Systems
Research
THE A. JAMES CLARK SCHOOL of ENGINEERING
UNIVERSITY OF MARYLAND