E3SM
Energy Exascale Earth System Model

Systems Engineering for Mission-Driven Modeling

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Big picture - E3SM today

- Coupled-system science questions drive E3SM development
- Strategic plan captures science questions and top-level requirements
- Project is decomposed as major science components and supporting technology components
- Component-level roadmapping exercises describe new development and integration
- Activity and progress tracked at multiple levels (epic, component, system)
- “Verification and validation” testing performed at multiple development and integration junctures
- System design decisions are made as needed, on the basis of testing and analysis

E3SM: Software project, or science mission?

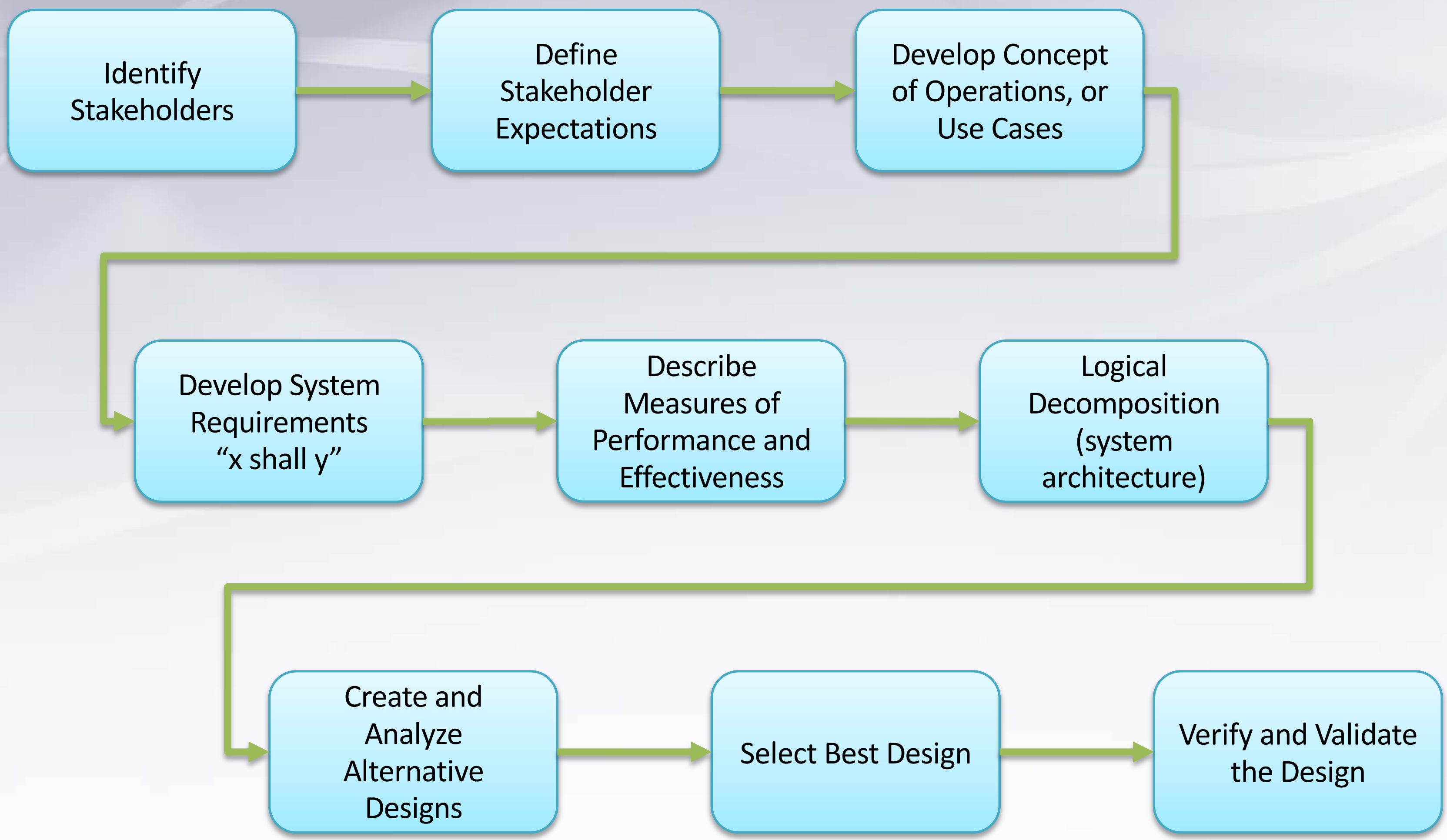
- Because our work is so focused on code development and testing, potential to view the effort in the context of large-scale software development.
- Alternative context: view E3SM as a science instrument built to answer one or more research questions.
- Examples instruments and science missions:
  - Laser Interferometer Gravitational-Wave Observatory (LIGO)
    - Directly observe gravitational waves of cosmic origin
  - Cassini Probe
    - Study Saturn, its rings, and moons
  - E3SM
    - Investigate the challenges posed by the interactions of weather-climate scale variability with energy and related sectors

Systems Engineering

- A methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system.
- The art and science of developing an operable system capable of meeting requirements within often opposed constraints.
- “System”: construct or collection of different elements that together produce results not obtainable by the elements alone.

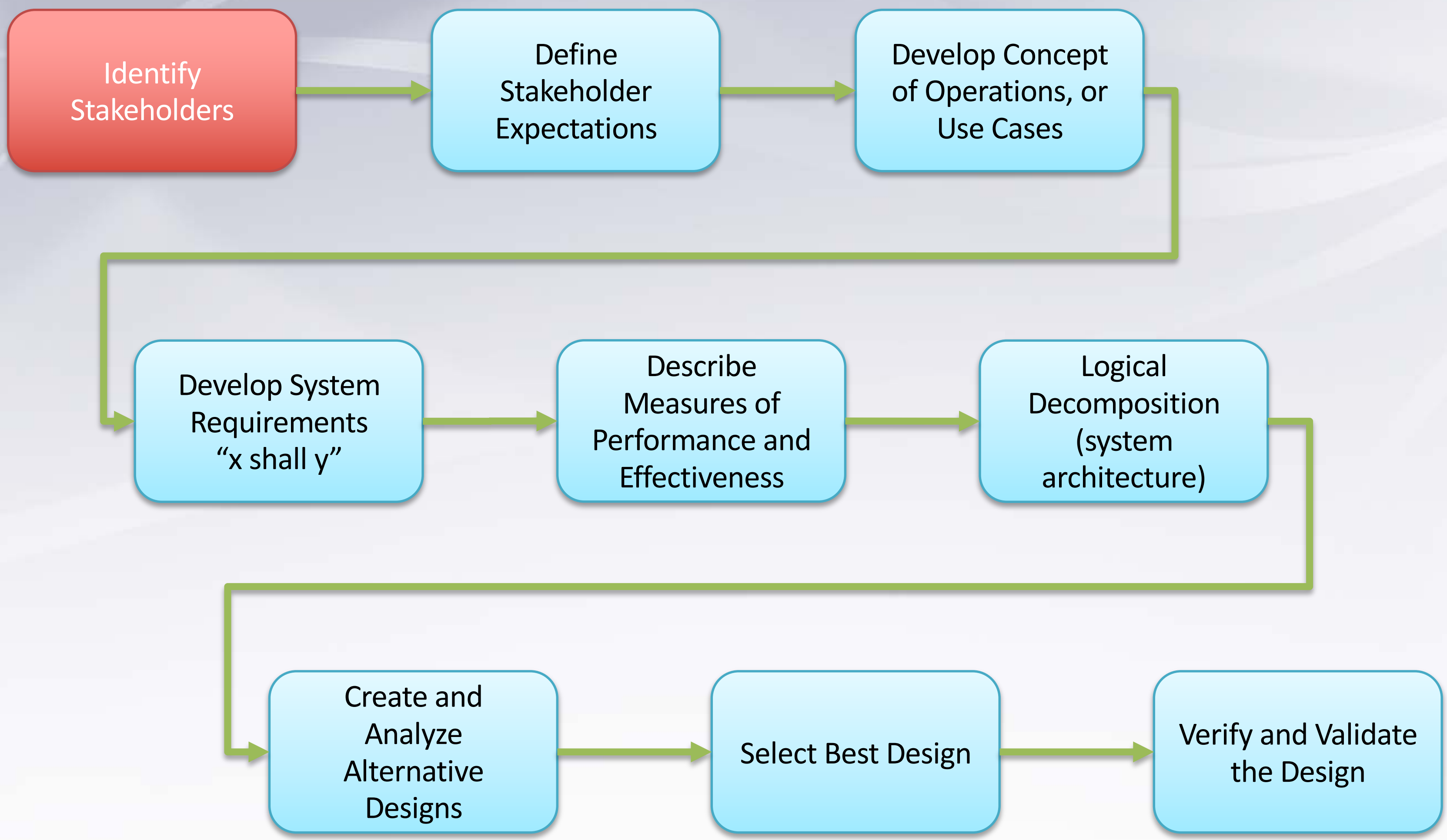
Also DoD, NNSA, ESA, other mission-oriented agencies.

Systems Engineering design process



The design process is ***iterative*** and ***recursive***

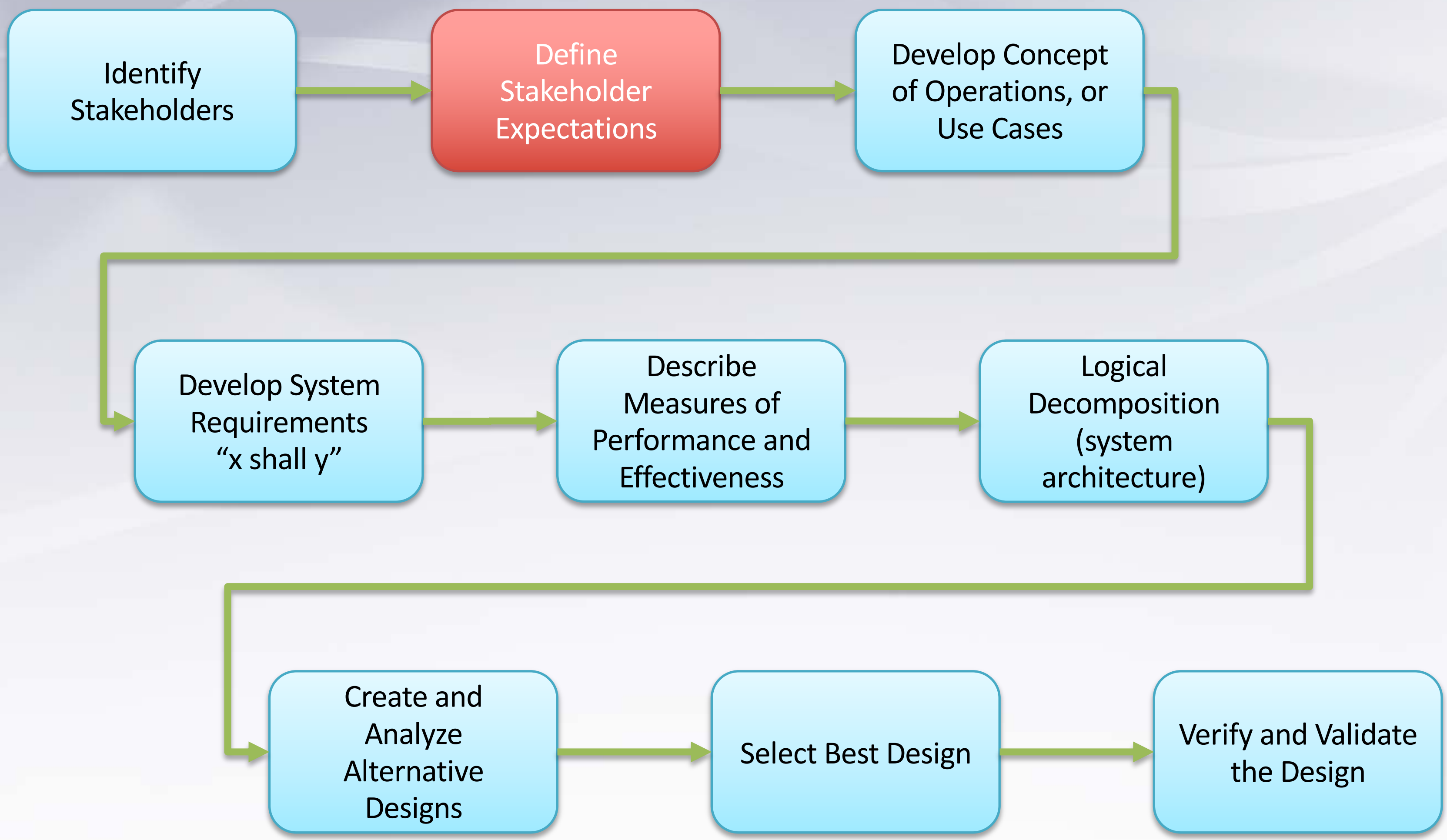
Systems Engineering design process



Identify Stakeholders

- Congress / OMB
- DOE Office of Science
- BER / CESD
- Executive Committee
- E3SM Domain Scientists
- E3SM Software Engineers
- Other interested parties
  - Partner projects and agencies
  - Earth system modeling community
  - General public

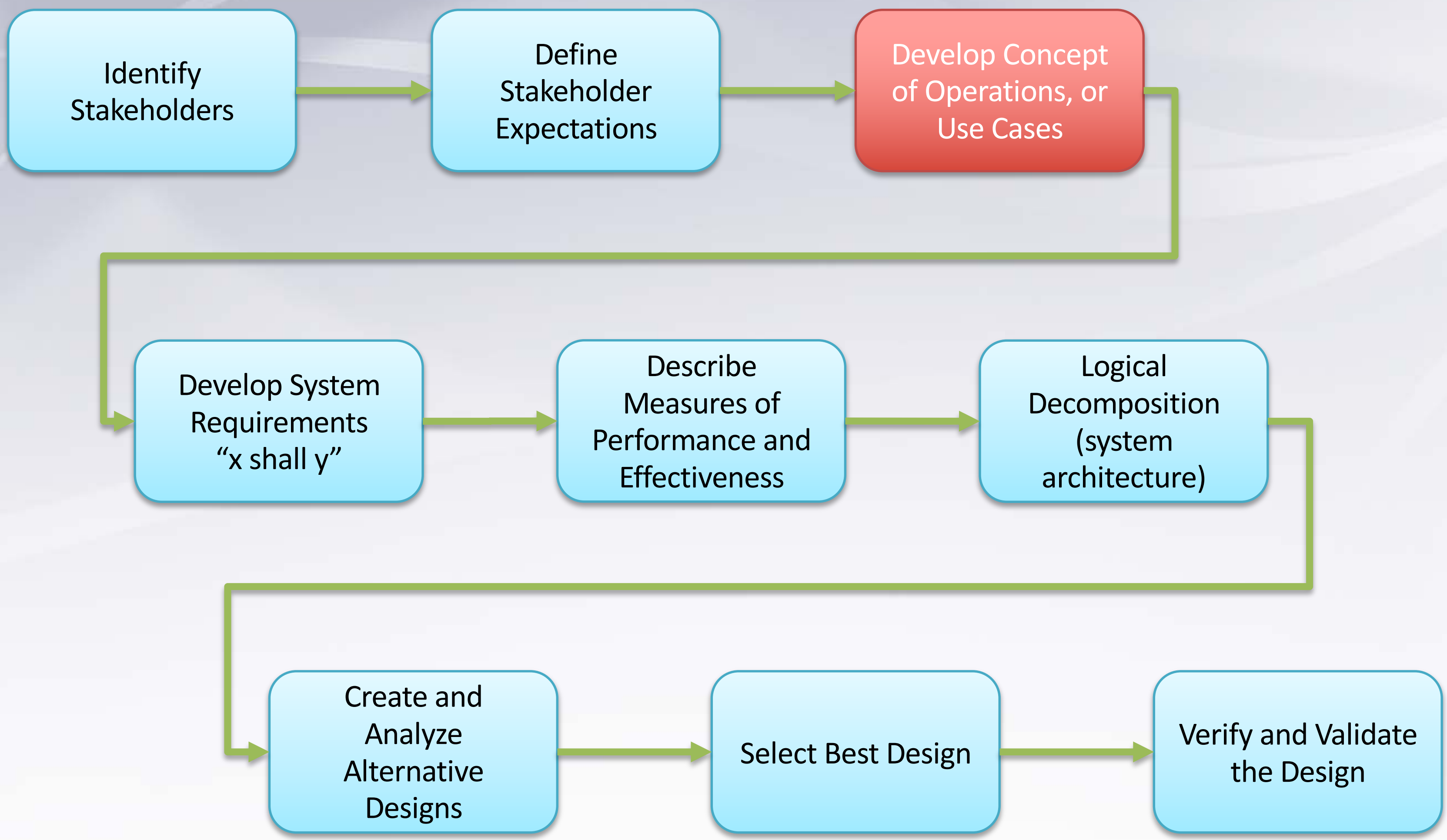
Systems Engineering design process



Define Stakeholder Expectations

- Budget language
- DOE, Office of Science mission statements
- BER / CESD Strategic Plans
- Authorizing language
- E3SM proposal, feedback
- E3SM Strategic Plans
- E3SM Executive Committee, Council+GL calls
- Group calls
- All-hands meetings
- **Results should be documented, and revisited frequently**

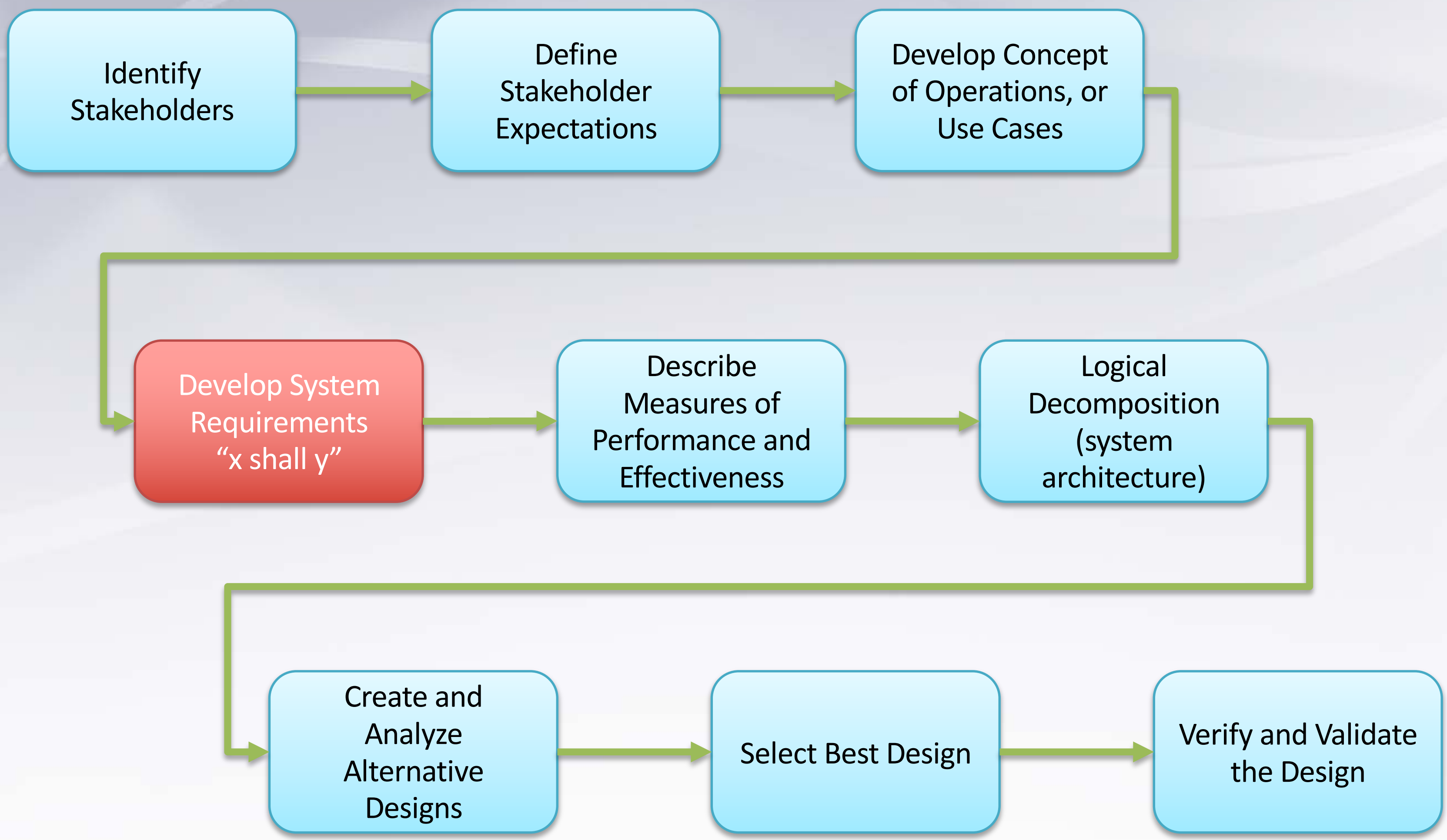
Systems Engineering design process



Develop "Concept of Operations"

- E3SM experiments serve as "design reference missions" around which use cases are developed
- Having these concepts well-developed early in the process helps translate expectations into design requirements
- Requires creative input from the whole team

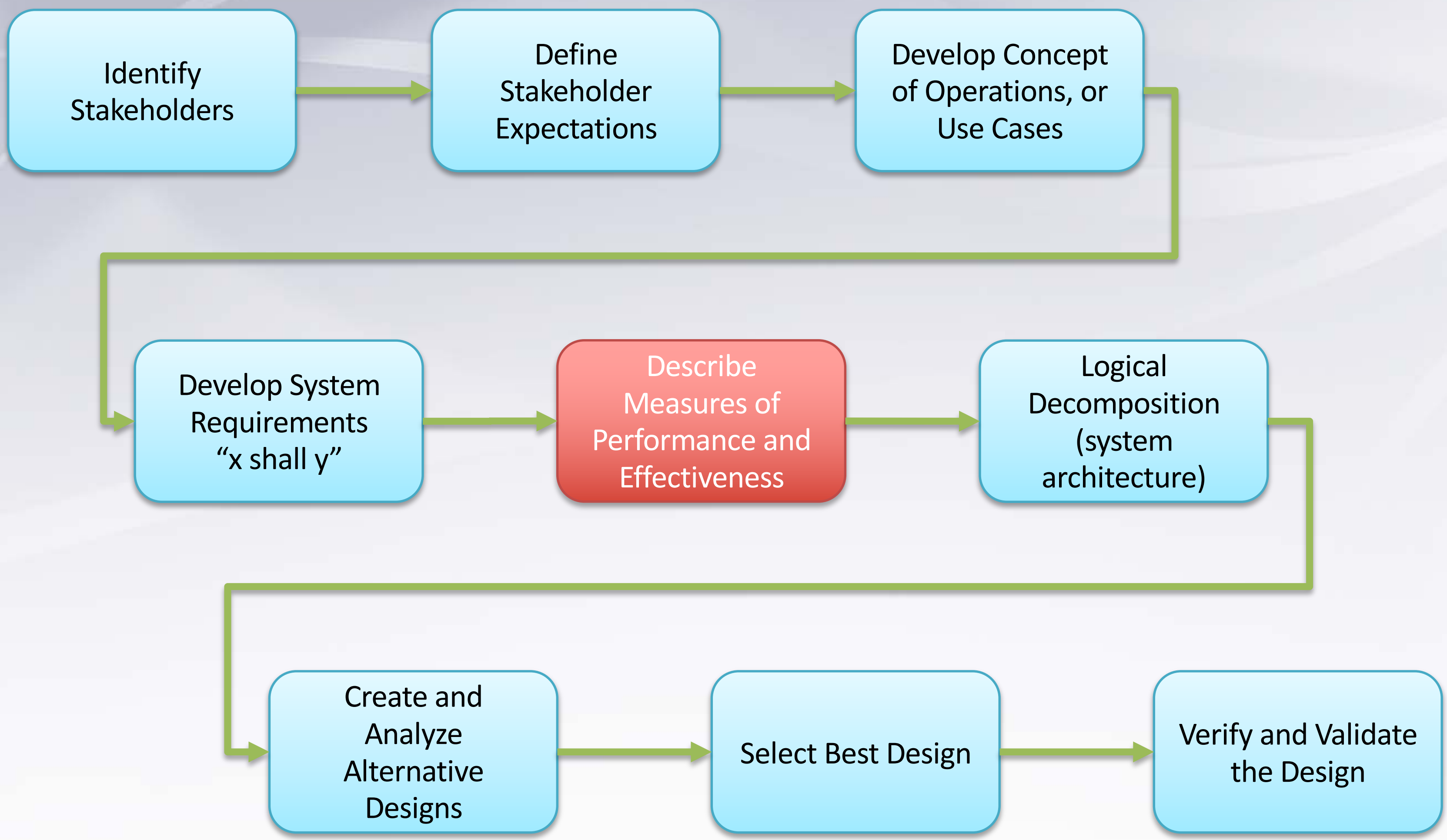
Systems Engineering design process



Develop System Requirements

- *What* the system shall do (not *how* it will do it)
- Definitive statements: “X shall Y”
  - “The coupled system shall perform at least 5 simulated years per day”
  - “The land and atmosphere components shall work together to represent topographic effects surface weather”
  - “The cycling of phosphorus shall be represented between land, ocean, and atmosphere components”
- Requirements flow down from higher levels, and are refined for each system level.

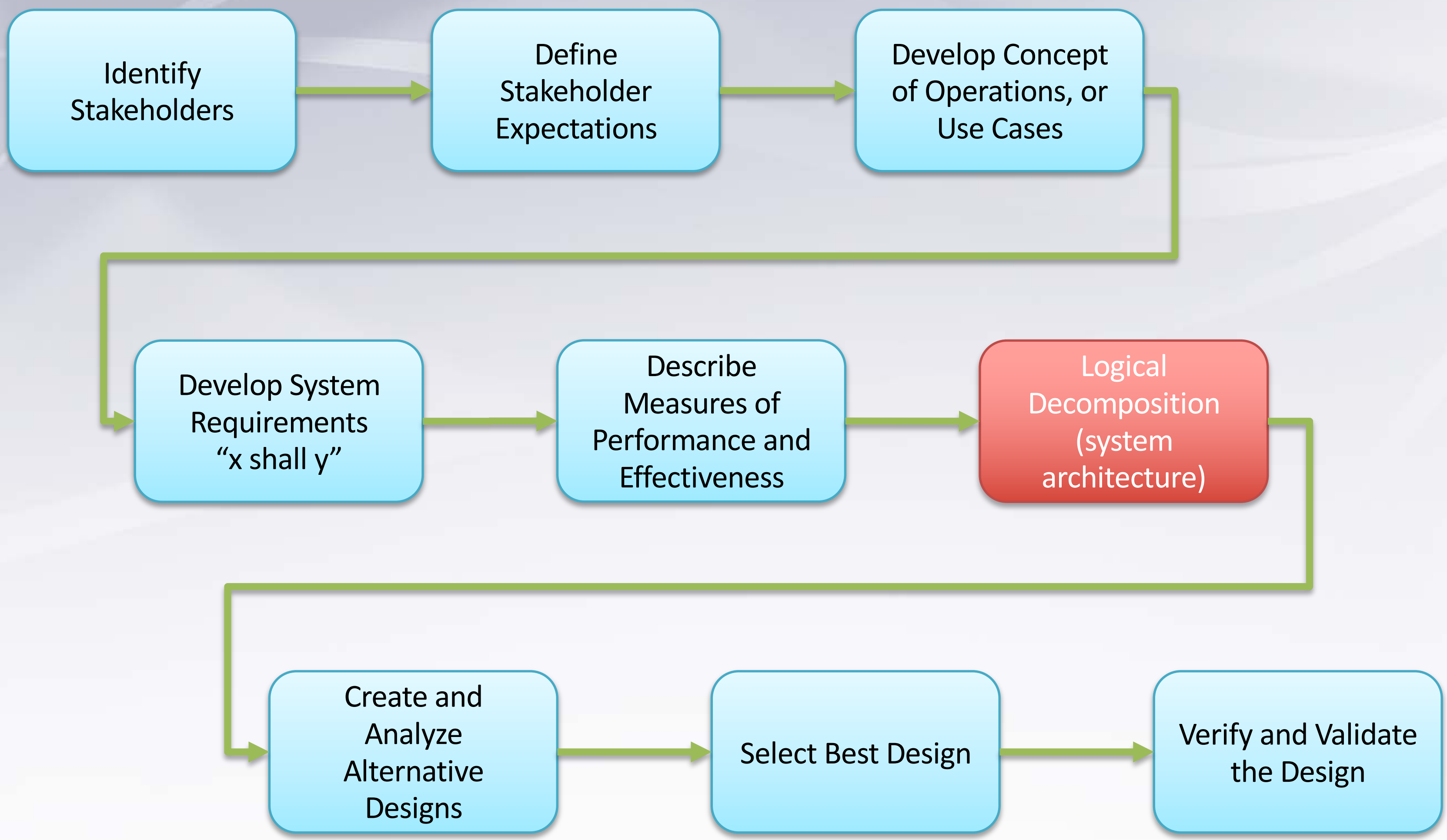
Systems Engineering design process



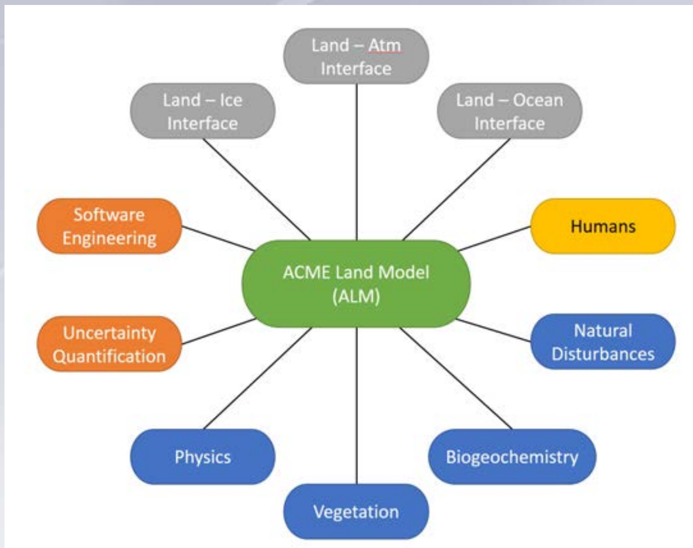
Metrics of Success

- Requirements should be as quantitative as possible
- Requirements should be only as restrictive as necessary
- Performance and effectiveness of candidate designs should be evaluated against ability to meet requirements
  - "ENSO variability shall be simulated within +/- x% of observed frequency and intensity…"
  - "Ocean temperatures shall be simulated within +/- x degrees C on global mean, +/- y degrees C on regional means…"
  - "Land albedo shall be simulated within +/- x% of remote sensing observations on global mean, +/- y% on regional means…"

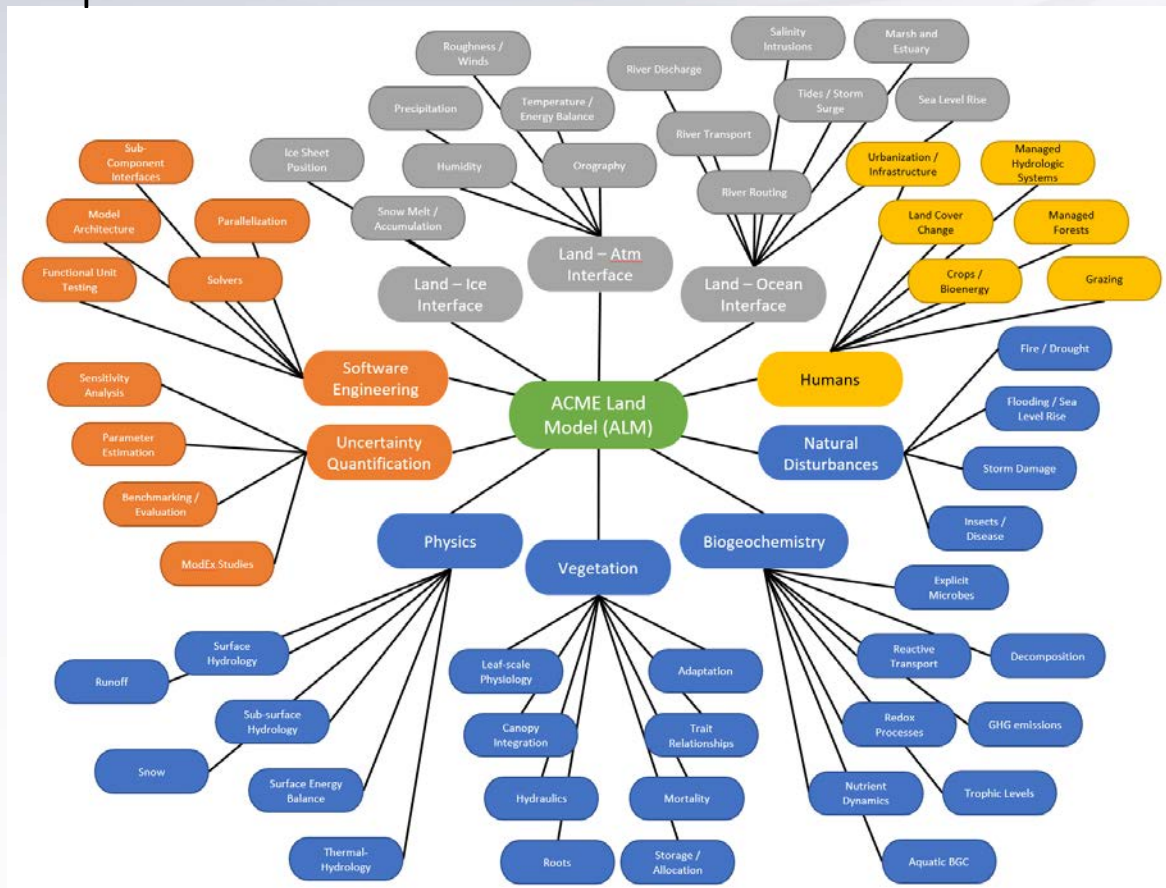
Systems Engineering design process



Logical Decomposition: system architecture

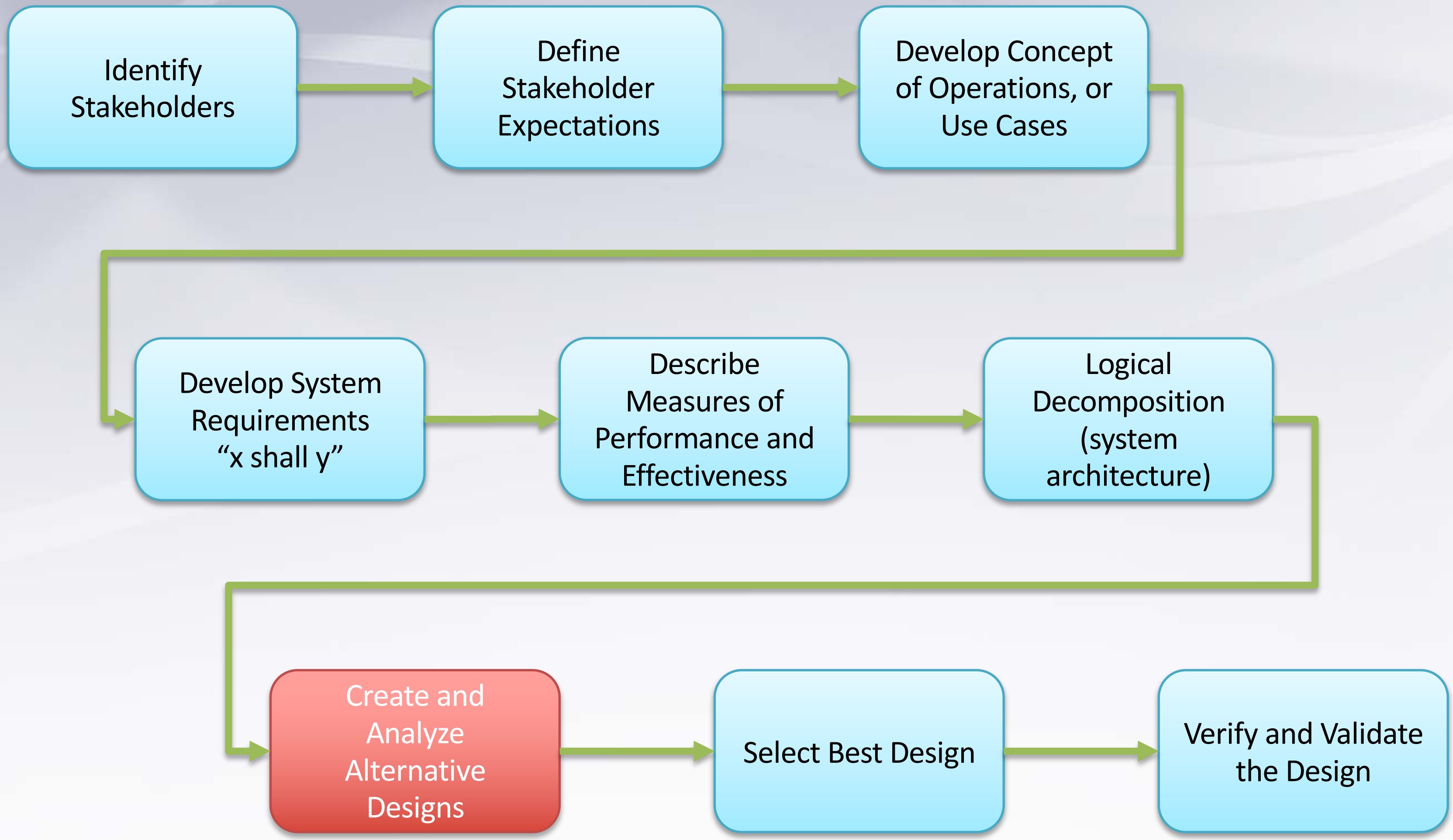


System architecture should be driven by stakeholder expectations, concept of operations, and system requirements



Opportunity for creativity and exploration: many potential architectures could meet requirements. Pursue alternatives to the extent allowable by schedule and budget.

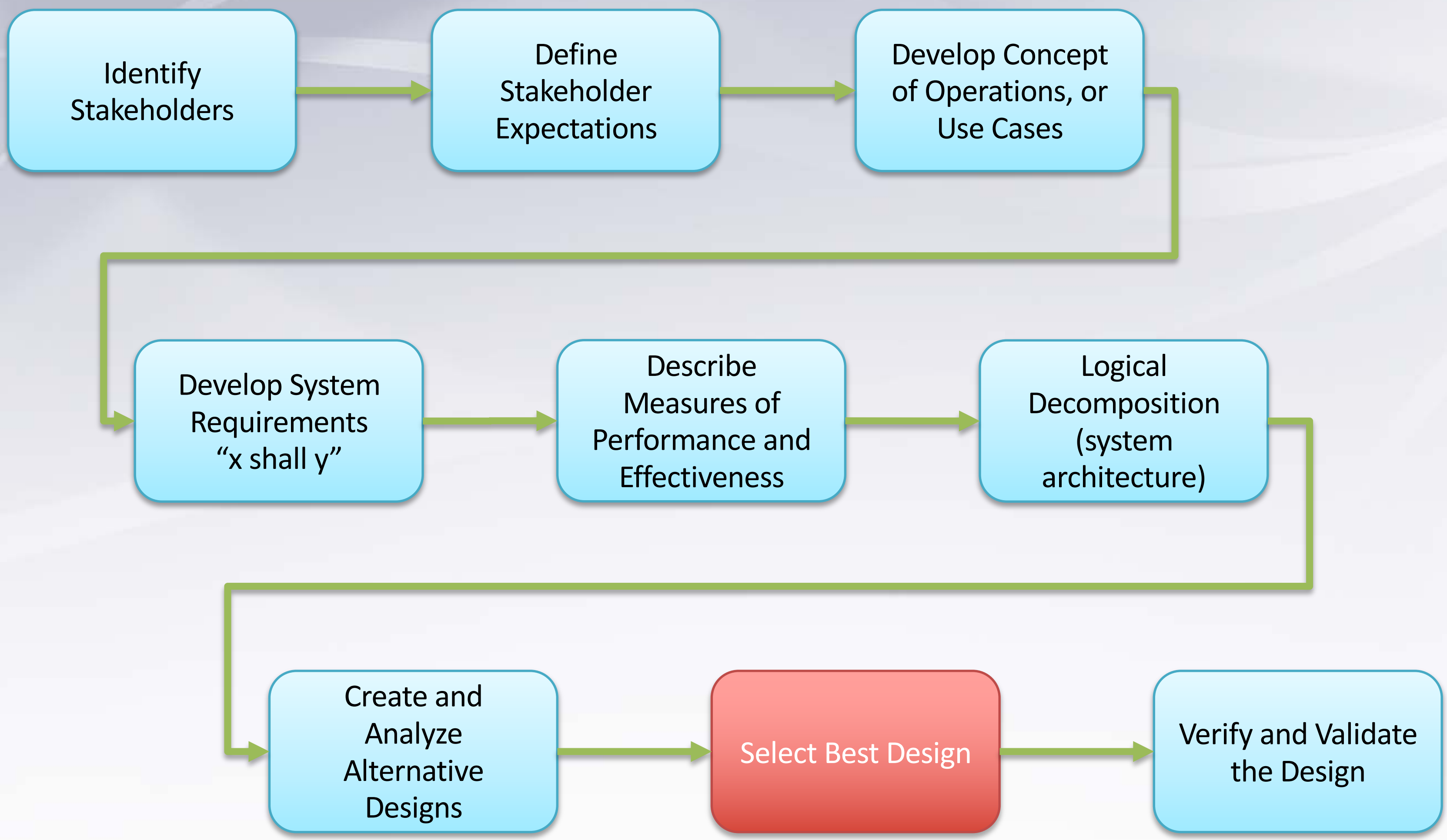
Systems Engineering design process



Create and analyze alternative designs

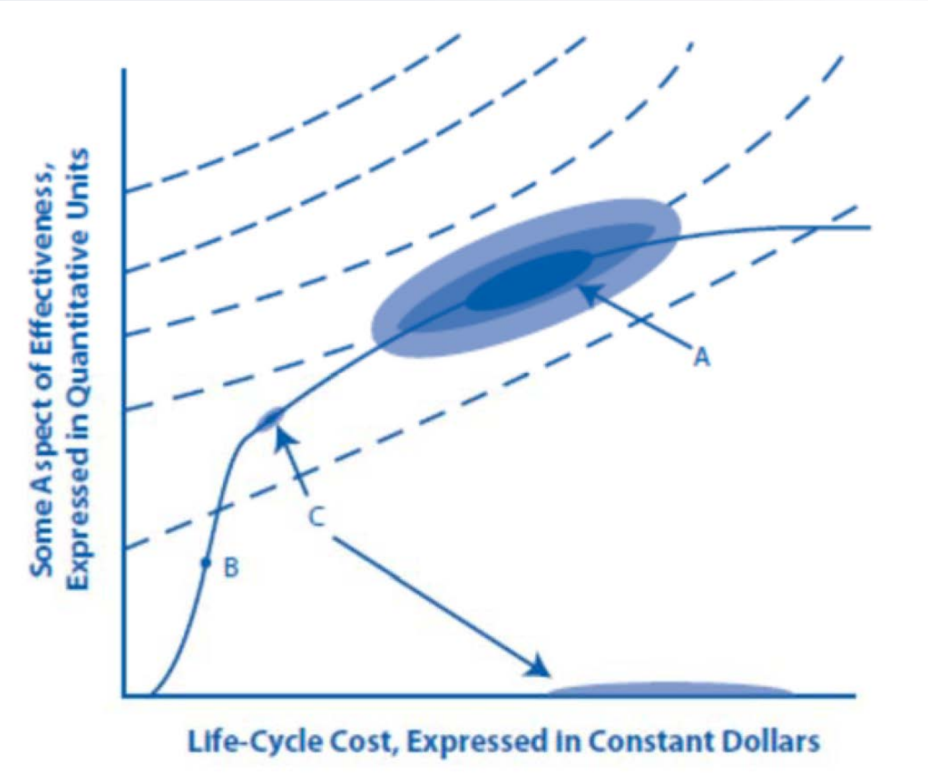
- Requirements “flowed down” to the lowest level of the current iteration of system architecture
- Design solutions to meet requirements
- Includes interface design to meet interface requirements connecting components across the architecture
- Explore as many alternative designs as allowable by schedule and budget, and as constrained by previous tradeoff studies

Systems Engineering design process

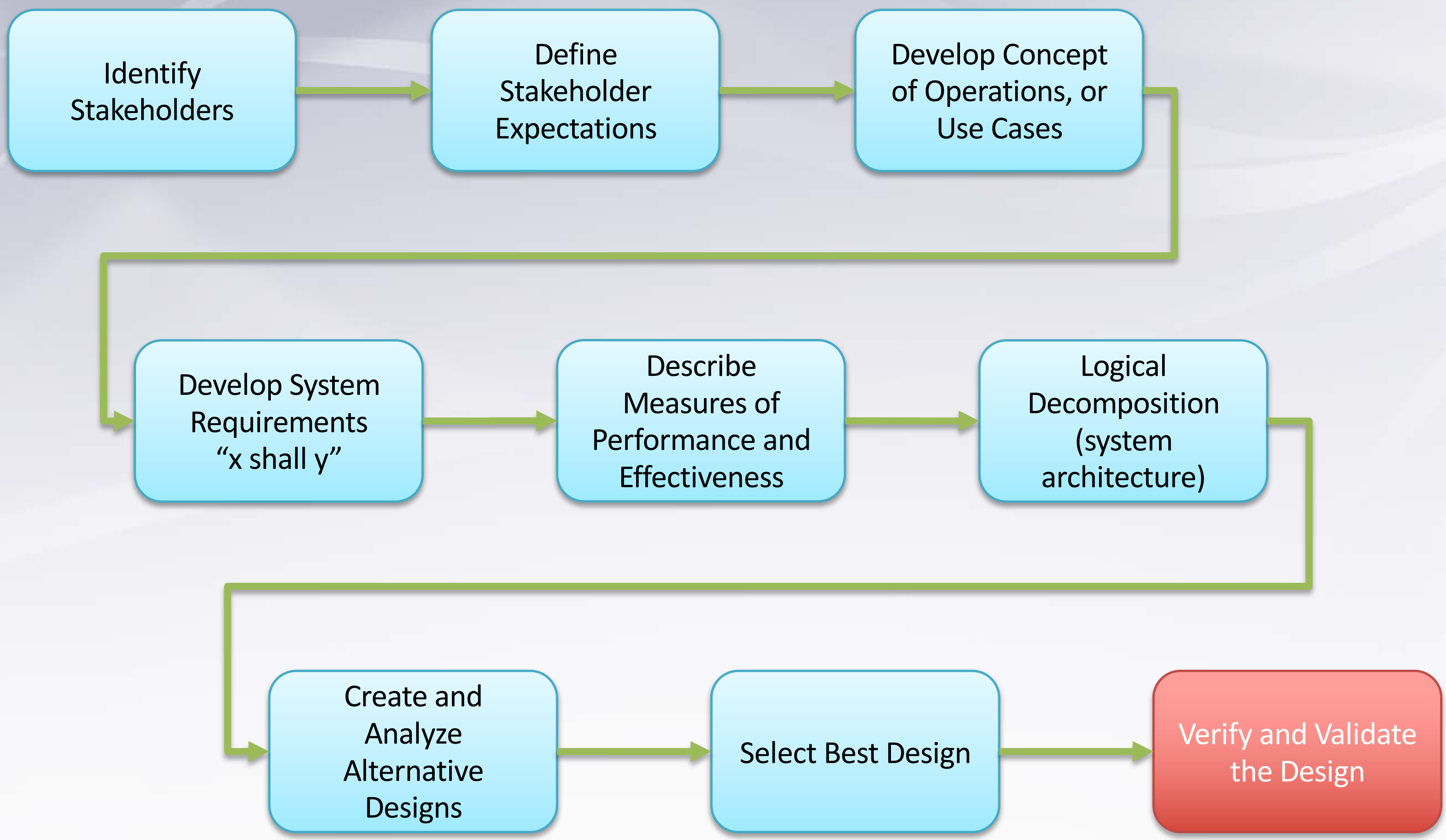


Select best design

- Meeting all requirements
- Evaluated against metrics of performance and effectiveness
- Tradeoff studies: cost-benefit analysis in an uncertain evaluation space
- Clear decision authority



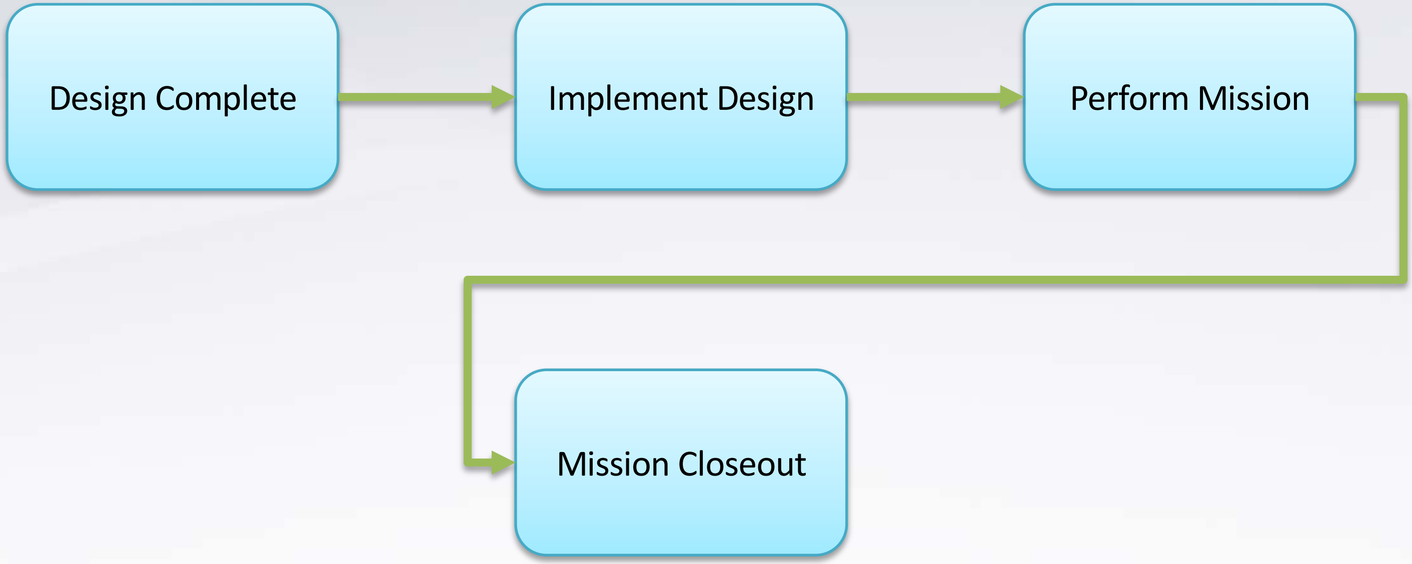
Systems Engineering design process



Verify and validate design

- This is done at every level of the system architecture
- Verification shows that the product meets all requirements
- Validation shows that the product accomplishes the intended purpose in the intended environment: meets the stakeholder expectations
  - Demonstrated through testing, analysis, inspection, and/or demonstration
- This marks the end of one iteration of the design process.
- Lessons learned inform new/modified expectations, requirements, metrics of success, architectures, and designs.

Further steps in Systems Engineering process



Summary

- E3SM is following many of the guiding principles of Systems Engineering already
- We might be able to communicate our approach more effectively (to ourselves and to our stakeholders) if we adopted some of the existing guidelines more explicitly
- We might increase efficiency and improve our end product by being more intentional about some steps of the process:
  - Documentation of expectations, concept of operations, and requirements
  - Attention to whole-system architecture
  - Explicit adoption of "iterative design before implementation"