

# CAS 741 (Development of Scientific Computing Software)

Winter 2023

## 05 Program Families

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# Program Families

- Administrative details
- Finish up SRS
- Specification Qualities
- Motivation for Families
- Proposed Family Methods
- Family of Linear Solvers
- Other examples (covered in “bonus” slides)
  - ▶ Family of Mesh Generators (in other set of slides)
  - ▶ Family of Material Behaviour Models (in other set of slides)

# Administrative Details

- Three projects have not been approved
- Primary reviewers and secondary reviewers
  - ▶ Ask at least one question after presentation
  - ▶ By two days after each major deliverable, create at least 5 GitHub issues
- Creating issues as a reviewer
  - ▶ **Please limit the number of issues related to formatting :-)**
  - ▶ Issues that are questions are fine
  - ▶ Example of question label
  - ▶ Example of “at”, and traceability
  - ▶ One issue, per issue
  - ▶ Connection to commit and pull request
  - ▶ screenshots, links, full description
  - ▶ Writing Checklist include advice on issue creation

# Administrative Details: Draft Report Deadlines

<b>System Req. Spec. (SRS)</b>	Week 04	Feb 3
System VnV Plan	Week 06	Feb 17
Module Guide (MG) + Mod Int Spec (MIS)	Week 09	Mar 17
Drasil Code (Drasil projects)	Week 09	Mar 17
Final Documentation	Week 13	Apr 12

- The written deliverables will be graded based on the repo contents as of 11:59 pm of the due date
- If you need an extension for a **written** doc, please ask
- When ready, assign issues to your primary and secondary reviewers
- GitHub issues due two days after assignment deadlines
- From Drasil Code onward, Drasil projects no longer need to maintain traditional SRS

# Administrative Details: Presentations (Draft Deadlines)

<b>SRS</b>	Week 03/04	Week of Jan 23, 30
Syst. VnV	Week 06	Week of Feb 13
POC Demo	Week 06, 07	Week of Feb 13, 27
MG + MIS Syntax	Week 09	Week of Mar 13
MIS Semantics	Week 09	Week of Mar 13
Unit VnV/Implement	Week 11/12	Week of Mar 27, Apr 3
Drasil	Week 11/12	Week of Mar 27, Apr 3

- Specific schedule depends on final class registration
- Informal presentations with the goal of improving everyone's written deliverables
- Domain experts and secondary reviewers (and others) will ask questions

# Tentative Presentation Schedule

- SRS Present (25 min)
  - ▶ **Jan 26: Jason, Sam, Mina**
  - ▶ **Feb 1: Deesha, Maryam, Karen**
  - ▶ **Feb 2: Zehong, Lesley, Joachim**
- Syst V&V Plan Present (25 min)
  - ▶ Feb 15: Sam, Jason, Zehong
- Proof of Concept Demonstrations (25 min)
  - ▶ Feb 16: Joachim, Lesley, Mina,
  - ▶ Mar 2: Maryam, Deesha, Karen
- MG Present (Drasil SRS Code) (15 minutes)
  - ▶ Mar 15: Maryam, Joachim, Karen, Sam, Zehong
- MIS Present (Drasil SRS Code) (15 min)
  - ▶ Mar 16: Jason, Lesley, Deesha, Mina
- Drasil Project Present (25 min each)
  - ▶ Mar 29: Zehong, Sam, Jason

# Tentative Presentation Schedule

- Test or Impl. Present (25 min each)
  - ▶ Apr 5: Lesley, Karen, Deesha
  - ▶ Apr 6: Mina, Joachim, Maryam
- 4 presentations each (please check)
- If you will miss a presentation, please trade with someone else

# Administrative Details: Presentations

- Presentations are about 25 minutes
- Informal
- HDMI and VGA connections in room
- To help you prepare your written document
- Questions from audience
- Grading out of 3
  - ▶ Generate discussion, evidence of thought, organized 3/3
  - ▶ Any element missing from above 2/3
  - ▶ Any two elements missing from above 1/3
  - ▶ No presentation 0/3



# SRS Presentations

- Project name
- Draft Goal statements
- Draft Assumptions
- Draft Input and output variables (data constraints)
- Draft General Definitions and Theoretical models
- Draft Instanced models
- Questions (from reviewers, instructor, anyone)

# Presentation Guidelines Continued

- Start all presentation with your project title and goal statements (not everyone in the audience will remember what you are doing)
- Time will go fast
  - ▶ You can gloss over domain details
  - ▶ Focus on the important/interesting things
  - ▶ Focus on questions that you have
  - ▶ You don't have to start at the "beginning" of any documents, get to the good stuff
  - ▶ Every slides should have  $x/\text{total slides}$  on it (so the moderator can judge whether you are going too fast or slow)
- Presentation slides should be under version control
- Presentation slides should be pushed well before class time
- The instructor will warn you when you have 5 minutes left

# More Example Projects

- Double Pendulum
- SpectrumImageAnalysisPy
- Conformer Searching using Evolutionary Computation
- Medical Image Segmentation
- Fourier Series
- Library of Lighting Models
- Scanning Transmission Electron Microscopy
- Chemical Speciation

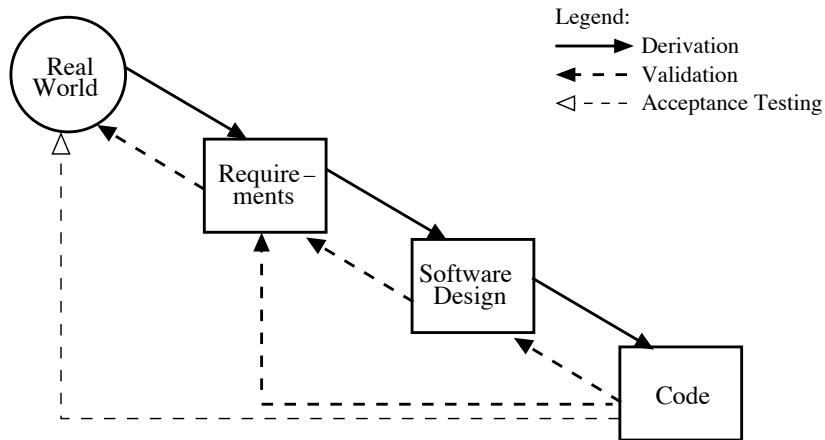
# Questions?

- Questions about SRS?
- Any questions on the [SRS Template](#)?
- Any questions on the [Writing Checklist](#)?
- Any questions on the [SRS Checklist](#)?
- Is  $a = \frac{dv}{dt}$  a TM or a DD?

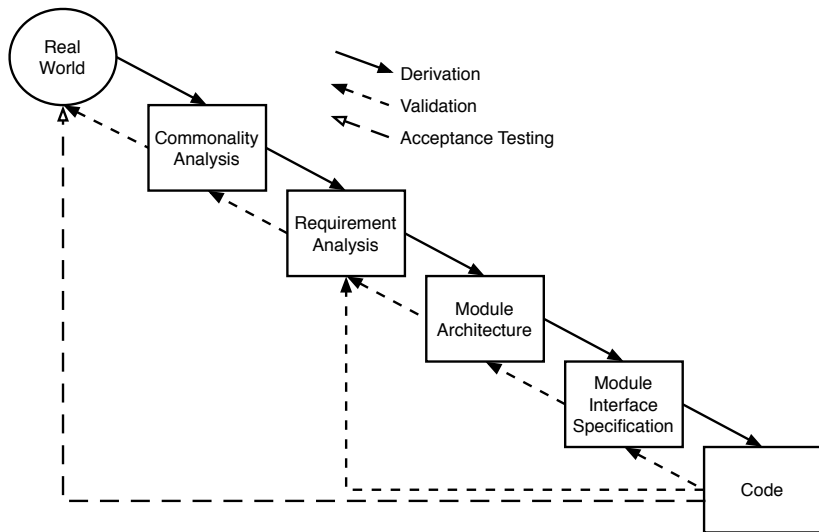
# Outline of Discussion of Requirements

- System Requirements Specification and template for beam analysis software
  - ▶ Provides guidelines
  - ▶ Eases transition from general to specific
  - ▶ Catalyses early consideration of design
  - ▶ Reduces ambiguity
  - ▶ Identifies range of model applicability
  - ▶ Clear documentation of assumptions

# A Rational Design Process



# Sometimes Include Commonality Analysis

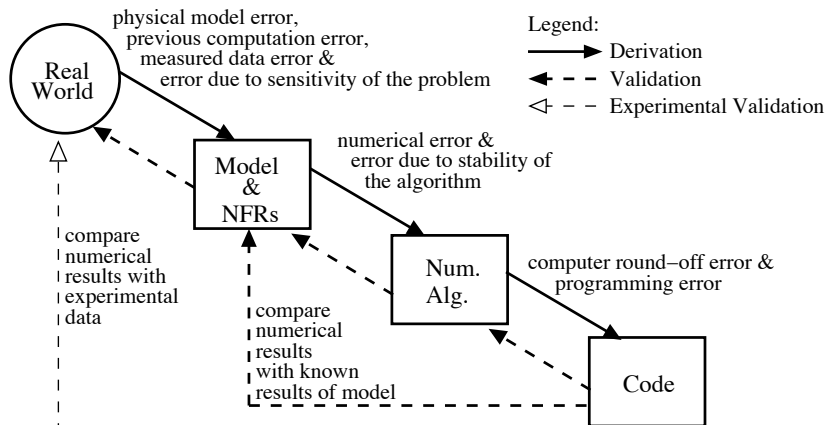


# Software Requirements Activities

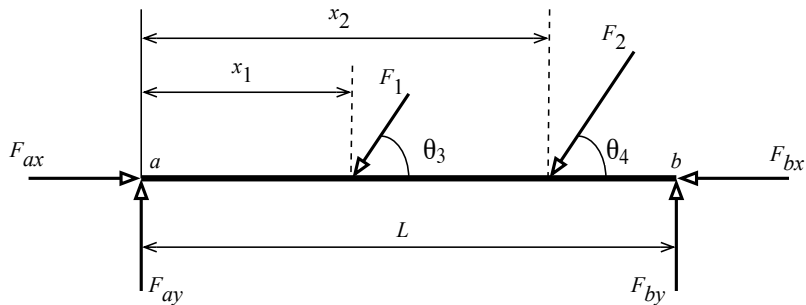
- A software requirement is a description of how the system should behave, or of a system property or attribute
- Requirements should be abstract, unambiguous, complete, consistent, modifiable, verifiable and traceable
- Requirements should express “What” not “How”
- Formal versus informal specification
- Functional versus nonfunctional requirements
- Software requirements specification (SRS)
- Requirements template



# Why Requirements Analysis?



# Beam Analysis Software



# Proposed Template

From [20]

1. Reference Material: a) Table of Symbols ...
2. Introduction: a) Purpose of the Document; b) Scope of the Software Product; c) Organization of the Document.
3. General System Description: a) System Context; b) User Characteristics; c) System Constraints.
4. Specific System Description:
  - 4.1 Problem Description: i) Background Overview ...
  - 4.2 Solution specification: i) Assumptions; ii) Theoretical Models; ...
  - 4.3 Non-functional Requirements: i) Accuracy of Input Data; ii) Sensitivity ...
5. Traceability Matrix
6. List of Possible Changes in the Requirements
7. Values of Auxiliary Constants

# Provides Guidance

- Details will not be overlooked, facilitates multidisciplinary collaboration
- Encourages a systematic process
- Acts as a checklist
- Separation of concerns
  - ▶ Discuss purpose separately from organization
  - ▶ Functional requirements separate from non-functional
- Labels for cross-referencing
  - ▶ Sections, physical system description, goal statements, assumptions, etc.
  - ▶ PS1.a “the shape of the beam is long and thin”

# Eases Transition from General to Specific

- “Big picture” first followed by details
- Facilitates reuse
- “Introduction” to “General System Description” to “Specific System Description”
- Refinement of abstract goals to theoretical model to instanced model
  - ▶ **G1**. Solve for the unknown external forces applied to the beam
  - ▶ **T1**  $\sum F_{xi} = 0, \sum F_{yi} = 0, \sum M_i = 0$
  - ▶ **M1**  $F_{ax} - F_1 \cdot \cos \theta_3 - F_2 \cdot \cos \theta_4 - F_{bx} = 0$

# Ensures Special Cases are Considered

$H_2$		$H_1$	
$S_{unkF} \notin \mathbb{P}_3$	-	$S_{GET} = S_{sym} - S_{unkF}$	$S_{GET} \neq (S_{sym} - S_{unkF})$
$S_{unkF} = \{\odot F_{ax}, \odot F_{bx}, \odot F_{ay}\}$	-	$(ErrorMsg' = InvalidUnknown) \wedge ChangeOnly(ErrorMessage)$	FALSE
$S_{unkF} = \{\odot F_{ax}, \odot F_{ay}, \odot F_1\}$	$x_1 \neq 0$ $\wedge \theta_3 \neq 0$ $\wedge \theta_3 \neq 180$	$ErrorMsg' = NoSolution \wedge ChangeOnly(ErrorMessage)$	
	otherwise	$F'_{ax} = \frac{-\cos \theta_3 F_2 x_2 \sin \theta_4 + \cos \theta_3 F_{by} L + F_2 \cos \theta_4 x_1 \sin \theta_3 + F_{bx} x_1 \sin \theta_3}{x_1 \sin \theta_3}$ $\wedge$ $F'_{ay} = -\frac{F_2 x_2 \sin \theta_4 - F_{by} L - F_2 \sin \theta_4 x_1 + F_{by} x_1}{x_1 \sin \theta_3}$ $\wedge F'_1 = \frac{-F_2 x_2 \sin \theta_4 + F_{by} L}{x_1 \sin \theta_3} \wedge ChangeOnly(S_{unkF})$	
		$(ErrorMsg' = Indeterminant) \wedge ChangeOnly(ErrorMessage)$	
$H_2$		$G$	

# Catalyses Early Consideration of Design

- Identification of significant issues early will improve the design
- Section for considering sensitivity
  - ▶ Conditioning?
  - ▶ Buckling of beam
- Non-functional requirements
  - ▶ Tradeoffs in design
  - ▶ Speed efficiency versus accuracy
- Tolerance allowed for solution:  $|\sum F_{xi}|/\sqrt{\sum F_{xi}^2} \leq \epsilon$
- Solution validation strategies (now in a separate document)
- List of possible changes in requirements

# Reduces Ambiguity

- Unambiguous requirements allow communication between experts, requirements review, designers do not have to make arbitrary decisions
- Tabular expressions allow automatic verification of completeness
- Table of symbols
- Abbreviations and acronyms
- Scope of software product and system context
- User characteristics
- Terminology definition and data definition
- Ends arguments about the relative merits of different designs



# Identifies Range of Model Applicability

- Clear documentation as to when model applies
- Can make the design specific to the problem
- Input data constraints are identified
  - ▶ Physically meaningful:  $0 \leq x_1 \leq L$
  - ▶ Maintain physical description: PS1.a,  $0 < h \leq 0.1L$
  - ▶ Reasonable requirements:  $0 \leq \theta_3 \leq 180$
- The constraints for each variable are documented by tables, which are later composed together
- $(\min_f \leq |F_{ax}| \leq \max_f) \wedge (|F_{ax}| \neq 0) \Rightarrow$   
 $\forall (FF | @FF \in S_F \cdot FF \neq 0 \wedge \frac{\max\{|F_{ax}|, |FF|\}}{\min\{|F_{ax}|, |FF|\}} \leq 10^{r_f})$

# Summary of Variables

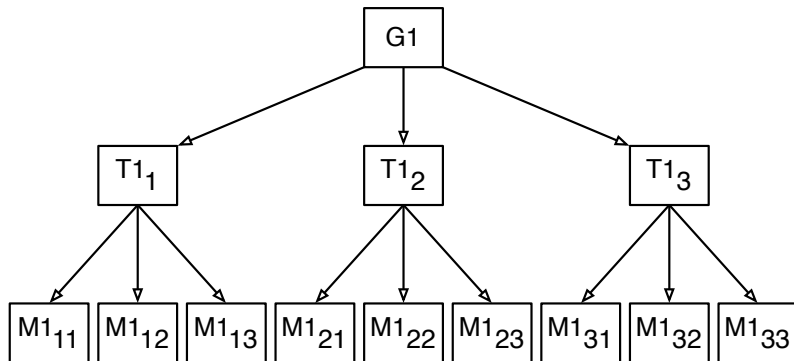
Var	Type	Physical Constraints	System Constraints	Prop
$x$	<i>Real</i>	$x \geq 0 \wedge x \leq L$	$\min_d \leq x \leq \max_d$	NIV
$x_1$	<i>Real</i>	$x_1 \geq 0 \wedge x_1 \leq L$	$\min_d \leq x_1 \leq \max_d$	IN
$x_2$	<i>Real</i>	$x_2 \geq 0 \wedge x_2 \leq L$	$\min_d \leq x_2 \leq \max_d$	IN
$e$	<i>Real</i>	$e > 0 \wedge e \leq h$	$\min_e \leq e \leq \max_e$	IN
$h$	<i>Real</i>	$h > 0 \wedge h \leq 0.1L$	$\min_h \leq h \leq \max_h$	IN
$L$	<i>Real</i>	$L > 0$	$\min_d \leq L \leq \max_d$	IN
$E$	<i>Real</i>	$E > 0$	$\min_E \leq E \leq \max_E$	IN
$\theta_3$	<i>Real</i>	$-\infty < \theta_3 < +\infty$	$0 \leq \theta_3 \leq 180$	IN
$\theta_4$	<i>Real</i>	$-\infty < \theta_4 < +\infty$	$0 \leq \theta_4 \leq 180$	IN
$V$	<i>Real</i>	$-\infty < V < +\infty$	-	OUT
$M$	<i>Real</i>	$-\infty < M < +\infty$	-	OUT
$y$	<i>Real</i>	$-\infty < y < +\infty$	-	OUT
...	...	...	...	...

# Clear Documentation of Assumptions

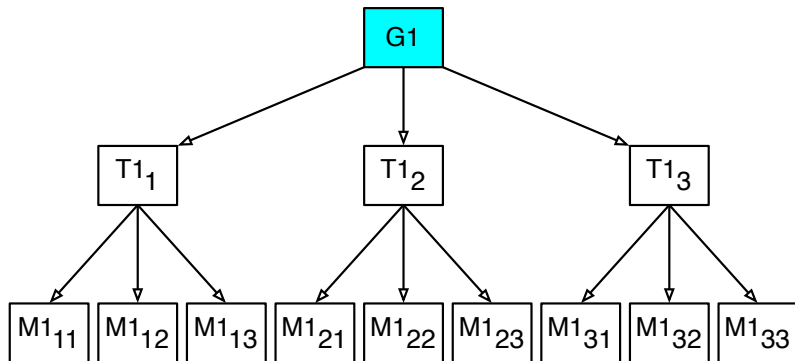
Phy. Sys. /Goal	Data /Model	Assumption										Model	
		A1	A2	...	A4	...	A8	A9	A10	...	A14	<b>M1</b>	...
<b>G1</b>	<b>T1</b>	✓		...		...	✓	✓		...		✓	...
<b>G2</b>	<b>T2</b>	✓		...		...	✓	✓		...			...
<b>G3</b>	<b>T3</b>	✓		...		...		✓	✓	...			...
	<b>M1</b>		✓	...		...				...		✓	...
PS1.a	<i>L</i>			...		...			✓	...		...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...

**A10.** The deflection of the beam is caused by bending moment only, the shear does not contribute.

# Refinement from Abstract to Concrete

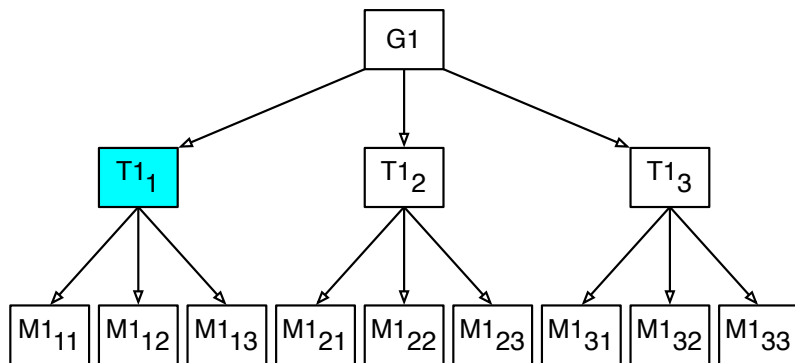


# Refinement from Abstract to Concrete



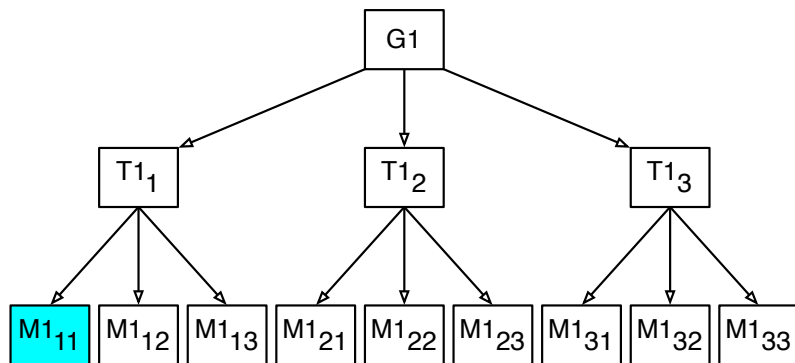
**G1:** Solve for unknown forces

# Refinement from Abstract to Concrete



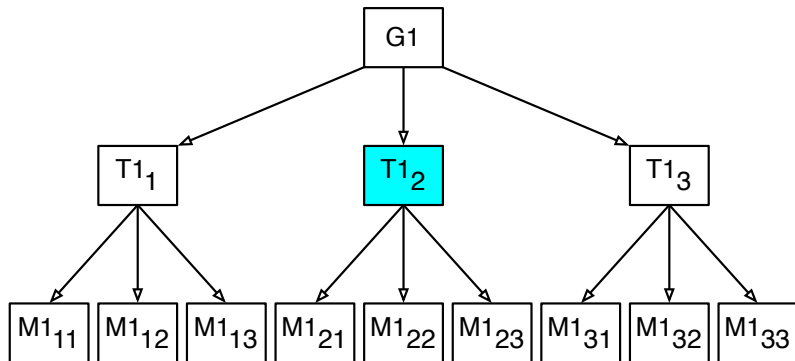
$$(\mathbf{T1_1}) \left\{ \begin{array}{l} \sum F_{xi} = 0 \\ \sum F_{yi} = 0 \\ \sum M_i = 0 \end{array} \right.$$

# Refinement from Abstract to Concrete



$$(M1) \quad \begin{cases} F_{ax} - F_1 \cdot \cos \theta_3 - F_2 \cdot \cos \theta_4 - F_{bx} = 0 \\ F_{ay} - F_1 \cdot \sin \theta_3 - F_2 \cdot \sin \theta_4 + F_{by} = 0 \\ -F_1 \cdot x_1 \sin \theta_3 - F_2 \cdot x_2 \sin \theta_4 + F_{by} \cdot L = 0 \end{cases}$$

# Refinement from Abstract to Concrete



The virtual work done by all the external forces and couples acting on the system is zero for each independent virtual displacement of the system, or mathematically  $\delta U = 0$



## Other goals and models

- **G2**: Solve for the functions of shear force and bending moment along the beam
- **G3**: Solve for the function of deflection along the beam
- **T3<sub>1</sub>**:  $\frac{d^2y}{dx^2} = \frac{M}{EI}$ ,  $y(0) = y(L) = 0$
- **T3<sub>2</sub>**:  $y$  determined by moment area method
- **T3<sub>3</sub>**:  $y$  determined using Castigliano's theorem
- **M3<sub>11</sub>**:  $y = \frac{12 \int_0^L (\int_0^L M dx) dx}{Eeh^3}$ ,  $y(0) = y(L) = 0$

# Kreyman and Parnas Five Variable Model

- See [8]
- An alternative approach
- Unfortunately the numerical algorithm is not hidden in the requirements specification
- The analogy with real-time systems leads to some confusion

# Links to Papers

- [SmithAndChen2004](#) [17] Commonality Analysis overview
- [SmithAndChen2004b](#) [16] CA example MG
- [SmithAndLai2005](#) [19] New requirements template
- [Smith2006](#) [14] General purpose tool template
- [SmithEtAl2007](#) [20] Template for SC audience
- [SmithAndKoothoor2016](#) [18] Nuclear fuelpin example
- [SmithEtAl2019\\_arXiv](#) [13] Debunk upfront myth
- [Smith2016](#) [15] Overview of artifacts
- [KreymanAndParnas2002](#) [8] 4 variable method

# Refined Theories Version

- Shortcomings of the template
  - ▶ Tedious to write and maintain (addressed by Drasil)
  - ▶ Three levels of refinement is arbitrary
  - ▶ Sloppy for notation ( $T$  should be  $T(t)$  etc.)
  - ▶ Assumptions are not systematically propagated
- Future refined theories version
  - ▶ Arbitrary levels of refinement
  - ▶ Pre and post conditions for theories
  - ▶ Assumptions are inherited
  - ▶ Proof (rationale) obligations for final theories
  - ▶ Example for **noPCM**

# Specification Qualities

- What are the important qualities for a specification?  
What makes a specification a good specification?

# Specification Qualities

- Clear, unambiguous, understandable
- Consistent
- Complete
  - ▶ Internal completeness
  - ▶ External completeness
- Incremental
- Validatable
- Abstract
- Traceable

Summarized in [18, p. 406]

# Clear, Unambiguous, Understandable

- Specification fragment for a word-processor
  - ▶ Selecting is the process of designating areas of the document that you want to work on. Most editing and formatting actions require two steps: first you select what you want to work on, such as text or graphics; then you initiate the appropriate action.
- What are the potential problems with this specification?

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- What are the potential problems with this specification?
  - ▶ Can an area be scattered?
  - ▶ Can both text and graphics be selected?



# Clear, Unambiguous, Understandable

- Specification fragment from a real safety-critical system
  - ▶ The message must be triplicated. The three copies must be forwarded through three different physical channels. The receiver accepts the message on the basis of a two-out-of-three voting policy.
- What is a potential problems with this specification?

# Clear, Unambiguous, Understandable

- Specification fragment from a real safety-critical system
  - ▶ The message must be triplicated. The three copies must be forwarded through three different physical channels. The receiver accepts the message on the basis of a two-out-of-three voting policy.
- What is a potential problems with this specification?
  - ▶ Can a message be accepted as soon as we receive 2 out of 3 identical copies, or do we need to wait for receipt of the 3rd

# Unambiguous, Validatable

- Specification fragment for an end-user program
  - ▶ The program shall be user friendly.
- What is a potential problems with this specification?

# Unambiguous, Validatable

- Specification fragment for an end-user program
  - ▶ The program shall be user friendly.
- What is a potential problems with this specification?
  - ▶ What does it mean to be user friendly?
  - ▶ Who is a typical user?
  - ▶ How would you measure success or failure in meeting this requirement?

# Unambiguous, Validatable

- Specification fragment for a linear solver
  - ▶ Given  $A$  and  $b$ , solve the linear system  $Ax = b$  for  $x$ , such that the error in any entry of  $x$  is less than 5 %.
- What is a potential problems with this specification?

# Unambiguous, Validatable

- Specification fragment for a linear solver
  - ▶ Given  $A$  and  $b$ , solve the linear system  $Ax = b$  for  $x$ , such that the error in any entry of  $x$  is less than 5 %.
- What is a potential problems with this specification?
  - ▶ Is  $A$  constrained to be square?
  - ▶ Can  $A$  be singular?
  - ▶ Even if the problem is made completely unambiguous, the requirement cannot be validated.

# Consistent

- Specification fragment for a word-processor
  - ▶ The whole text should be kept in lines of equal length. The length is specified by the user. Unless the user gives an explicit hyphenation command, a carriage return should occur only at the end of a word.
- What is a potential problems with this specification?

# Consistent

- Specification fragment for a word-processor
  - ▶ The whole text should be kept in lines of equal length. The length is specified by the user. Unless the user gives an explicit hyphenation command, a carriage return should occur only at the end of a word.
- What is a potential problems with this specification?
  - ▶ What if the length of a word exceeds the length of the line?



# Same Symbol/Term Different Meaning

- Can you think of some symbols/terms that have different meanings depending on the context?

# Consistent

- Language and terminology must be consistent within the specification
- Potential problem with homonyms, for instance consider the symbol  $\sigma$ 
  - ▶ Represents standard deviation
  - ▶ Represents stress
  - ▶ Represents the Stefan-Boltzmann constant (for radiative heat transfer)
- Changing the symbol may be necessary for consistency, but it could adversely effect understandability
- Potential problem with synonyms
  - ▶ Externally funded graduate students, versus eligible graduate students, versus non-VISA students
  - ▶ Material behaviour model versus constitutive equation

# Complete

- Internal completeness
  - ▶ The specification must define any new concept or terminology that it uses
    - ▶ A glossary is helpful for this purpose
- External completeness
  - ▶ The specification must document all the needed requirements
    - ▶ Difficulty: when should one stop?

# Incremental

- Referring to the specification process
  - ▶ Start from a sketchy document and progressively add details
  - ▶ A document template can help with this
- Referring to the specification document
  - ▶ Document is structured and can be understood in increments
  - ▶ Again a document template can help with this

# Traceable

- Explicit links
  - ▶ Within document
  - ▶ Between documents
- Use labels, cross-references, traceability matrices
- Common sense suggests traceability improves maintainability
- Shows consequence of change
- Minimizes cost of recertification
- Additional advantages
  - ▶ Program comprehension
  - ▶ Impact analysis
  - ▶ Reuse
- Why is traceability important?

# Accuracy Versus Precision



A



B



C



D

What is the distinction between accuracy and precision?

# Program Family Examples



# Program Families

- Can think of general purpose (or multi-purpose) SC software as a program family
- Some examples of physical models are also appropriate for consideration as a family
- A program family is a set of programs where it makes more sense to develop them together as opposed to separately
- Analogous to families in other domains
  - ▶ Automobiles
  - ▶ Computers
  - ▶ ...
- Need to identify the commonalities
- Need to identify the variabilities
- Discussed in general in [5, 12]



# Background

- Program family idea since the 1970s (Dijkstra, Parnas, Weiss, Pohl, ...) - variabilities are often from a finite set of simple options [10, 11, 7]
- Families of algorithms and code generation in SC (Carette, ATLAS, Blitz++, ...) - not much emphasis on requirements [4, 27, 23, 3]
- Work on requirements for SC
  - ▶ Template for a single physical model [20, 19]
  - ▶ Template for a family of multi-purpose tool [14, 17, 16]
  - ▶ Template for a family of physical models [22, 21, 9]

# Motivation

- Requirements documentation
  - ▶ Allows judgement of quality
  - ▶ Improves communication
    - ▶ Between domain experts
    - ▶ Between domain experts and programmers
    - ▶ Explicit assumptions
    - ▶ Range of applicability
- A family approach, potentially including a DSL to allow generation of specialized programs
  - ▶ Improves efficiency of product and process
  - ▶ Facilitates reuse of requirements and design, which improves reliability
  - ▶ Improves usability and learnability
  - ▶ Clarifies the state of the art

# Advantages of Program Families to SC?

- Usual benefits
  - ▶ Reduced development time
  - ▶ Improved quality
  - ▶ Reduced maintenance effort
  - ▶ Increased ability to cope with complexity
- Reusability
  - ▶ Underused potential for reuse in SC
  - ▶ Reuse commonalities
  - ▶ Systematically handle variabilities
- Usability
  - ▶ Documentation often lacking in SC
  - ▶ Documentation part of program family methodology
  - ▶ Create family members that are only as general purpose as necessary
- Improved performance

# Is SC Suited to a Program Family Approach?

Based on criteria from Weiss [2, 25, 26, 6, 24]

- The redevelopment hypothesis
  - ▶ A significant portion of requirements, design and code should be common between family members
  - ▶ Common model of software development in SC is to rework an existing program
  - ▶ Progress is made by removing assumptions
- The oracle hypothesis
  - ▶ Likely changes should be predictable
  - ▶ Literature on SC, example systems, mathematics
- The organizational hypothesis
  - ▶ Design so that predicted changes can be made independently
  - ▶ Tight coupling between data structures and algorithms
  - ▶ Need a suitable abstraction

# Challenges

## 1. Validatable

- ▶ Requirements can be complete, consistent, traceable and unambiguous, but still not validatable
- ▶ Input and outputs are continuously valued variables
- ▶ Correct solution is unknown a priori
- ▶ Given  $dy/dt = f(t, y)$  and  $y(t_0) = y_0$ , find  $y(t_n)$

## 2. Abstract

- ▶ If too abstract, then difficult to meet NFRs for accuracy and speed
- ▶ Assumptions can help restrict scope, but possibly as much work as solving the original problem
  - ▶  $Ax = b$
  - ▶  $x^T Ax > 0, \forall x$
- ▶ Algorithm selection should occur at the design stage

# Challenges (Continued)

## 3. Nonfunctional requirements

- ▶ Proving accuracy requirements with a priori error analysis is a difficult mathematical exercise that generally leads to weak error bounds
- ▶ Context sensitive tradeoffs between NFRs can be difficult to specify
- ▶ Absolute quantitative requirements are often unrealistic

## 4. Capture and Reuse Existing Knowledge

- ▶ Cannot ignore the enormous wealth of information that currently exists
- ▶ A good design will often involve integrating existing software libraries
- ▶ Reuse software and the requirements documentation

# Goal Statements for a Family of Linear Solvers?

What would be a good goal statement for a library of linear solvers?

# Goal Statements for a Family of Linear Solvers

- G1 Given a system of  $n$  linear equations represented by matrix  $A$  and column vector  $b$ , return  $x$  such that  $Ax = b$ , if possible



# Theoretical Model for a Family of Linear Solvers?

- Is the theoretical model a commonality or a variability?
- What is the theoretical model for a family of linear solvers?

# Theoretical Model for a Family of Linear Solvers

Given a square matrix  $A$  and column vector  $b$ , the possible solutions for  $x$  are as follows:

1. A unique solution  $x = A^{-1}b$ , if  $A$  is nonsingular
2. An infinite number of solutions if  $A$  is singular and  $b \in \text{span}(A)$
3. No solution if  $A$  is singular and  $b \notin \text{span}(A)$

[1]

# Instance Model for a Family of Linear Solvers?

- Is there an instance model for a family of linear solvers?

# Symbols and Terminology for a Family of Linear Solvers?

- What symbols and terminology will you need to define?

# Sample Symbols and Terminology

$n : \mathbb{N}$	number of linear equations/number of unknowns
$A : \mathbb{R}^{n \times n}$	$n \times n$ real matrix
$x : \mathbb{R}^{n \times 1}$	$n \times 1$ real column vector
$b : \mathbb{R}^{n \times 1}$	$n \times 1$ real column vector
$I : \mathbb{R}^{n \times n}$	an $n \times n$ matrix where all entries are 0, except for the diagonal entries, which are 1
$\ v\ $	the norm (estimate of magnitude) of vector $v$
$A^{-1} : \mathbb{R}^{n \times n}$	the inverse matrix, with the property that $A^{-1}A = I$
singular	matrix $A$ is singular if $A^{-1}$ does not exist
residual	$\ b - Ax\ $

# What Would be the Most General Binding Time?

- What would be the most general binding time for the variabilities?

# What Are Some Potential Input Variabilities?

- What are some potential input variabilities? What are the associated parameters of variation?

<b>Variability</b>	<b>Parameter of Variation</b>
Allowed structure of $A$	Set of { full, sparse, banded, tridiagonal, block triangular, block structured, diagonal, upper triangular, lower triangular, Hessenberg }
Allowed definiteness for $A$	Set of { not definite, positive definite, positive semi-definite, negative definite, negative semi-definite }
Allowed class of $A$	Set of { diagonally dominant, Toeplitz, Vandermonde }
Symmetric?	boolean
Values for $n$	set of $\mathbb{N}$
Entries in $A$	set of $\mathbb{R}$
Entries in $b$	set of $\mathbb{R}$



<b>Variability</b>	<b>Parameter of Variation</b>
Source of input	Set of { from a file, through the user interface, passed in memory }
Encoding of input	Set of {binary, text }
Format of input $A$	Set of {arbitrary, by row, by column, by diagonal }
Format of input $b$	Set of {arbitrary, ordered }

# What Are Some Potential Output Variabilities?

- What are some potential output variabilities? What are the associated parameters of variation?

# Output Variabilities

<b>Variability</b>	<b>Parameter of Variation</b>
Destination for output $x$	Set of { to a file, to the screen, to memory }
Encoding of output $x$	Set of {binary, text }
Format of output $x$	Set of {arbitrary, ordered }
Output residual	boolean (true if the program returns the residual)
Possible entries in $x$	set of $\mathbb{R}$

# What Are Some Potential Calculation Variabilities?

- What are some potential calculation variabilities? What are the associated parameters of variation?

# Calculation Variabilities

<b>Variability</b>	<b>Parameter of Variation</b>
Check input?	boolean (false if the input is assumed to satisfy the input assumptions)
Exceptions generated?	boolean (false if the goal is non-stop arithmetic)
Norm used for residual	Set of {1-norm, 2-norm, $\infty$ -norm }

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