Software Metrics and Design Principles

What is Design?

- Design is the process of creating a plan or blueprint to follow during actual construction
- Design is a problem-solving activity that is iterative in nature
- In traditional software engineering the outcome of design is the **design document** or **technical specification** (if emphasis on notation)

“Wicked Problem”

- Software design is a “Wicked Problem”
  - Design phase can’t be solved in isolation
    - Designer will likely need to interact with users for requirements, programmers for implementation
  - No stopping rule
    - How do we know when the solution is reached?
  - Solutions are not true or false
    - Large number of tradeoffs to consider, many acceptable solutions
  - Wicked problems are a symptom of another problem
    - Resolving one problem may result in a new problem elsewhere; software is not continuous

Systems-Oriented Approach

- The central question: how to decompose a system into parts such that each part has lower complexity than the system as a whole, while the parts together solve the user’s problem?
- In addition, the interactions between the components should not be too complicated
- Vast number of design methods exist

Design Considerations

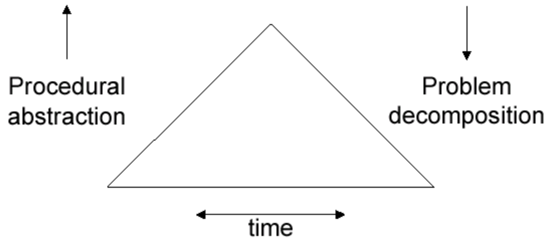
- "Module" used often – usually refers to a method or class
- In the decomposition we are interested in properties that make the system flexible, maintainable, reusable
  - Information Hiding
  - System Structure
  - Complexity
  - Abstraction
  - Modularity

Abstraction

- Abstraction
  - Concentrate on the essential features and ignore, abstract from, details that are not relevant at the level we are currently working on
  - E.g. Sorting Module
    - Consider inputs, outputs, ignore details of the algorithms until later
  - Two general types of abstraction
    - Procedural Abstraction
    - Data Abstraction

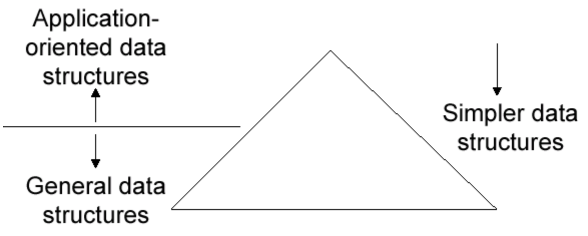
Procedural Abstraction

- Fairly traditional notion
  - Decompose problem into sub-problems, which are each handled in turn, perhaps decomposing further into a hierarchy
  - Methods may comprise the sub-problems and sub-modules, often in time



Data Abstraction

- From primitive to complex to abstract data types
  - E.g. Integers to Binary Tree to Data Store for Employee Records
- Find hierarchy in the data



Modularity

- During design the system is decomposed into modules and the relationships among modules are indicated
- Two structural design criteria as to the "goodness" of a module
  - Cohesion : Glue for intra-module components
  - Coupling : Strength of inter-module connections

Levels of Cohesion

1. Coincidental
   - Components grouped in a haphazard way
2. Logical
   - Tasks are logically related; e.g. all input routines. Routines do not invoke one another.
3. Temporal
   - Initialization routines; components independent but activated about the same time
4. Procedural
   - Components that execute in some order
5. Communicational
   - Components operate on the same external data
6. Sequential
   - Output of one component serves as input to the next component
7. Functional
   - All components contribute to one single function of the module
   - Often transforms data into some output format

Using Program and Data Slices to Measure Program Cohesion

- Bieman and Ott introduced a measure of program cohesion using the following concepts from program and data slices:
  - A data token is any variable or constant in the module
  - A slice within a module is the collection of all the statements that can affect the value of some specific variable of interest.
  - A data slice is the collection of all the data tokens in the slice that will affect the value of a specific variable of interest.
  - Glue tokens are the data tokens in the module that lie in more than one data slice.
  - Super glue tokens are the data tokens in the module that lie in every data slice of the program

Measure Program Cohesion through 2 metrics:

- weak functional cohesion = (# of glue tokens) / (total # of data tokens)
- strong functional cohesion = (#of super glue tokens) / (total # of data tokens)

Procedure Sum and Product

```
(N  : Integer;
 Var   SumN, ProdN : Integer);
Var              I  : Integer
Begin
   SumN        : = 0;
   ProdN       : = 1;
   For  I      : =  1  to   N   do begin
        SumN : =    SumN   +   I
        ProdN: =   ProdN    *   I
   End;
End;
```

Data Slice for SumN

```
( N  : Integer;
 Var   SumN, ProdN : Integer);
Var              I  : Integer
Begin
    SumN        : = 0;
    ProdN       : = 1;
    For  I      : =  1  to  N   do begin
         SumN : =    SumN   +   I
         ProdN: =   ProdN    *   I
    End;
End;
```

Data Slice for SumN = $N_1 \cdot SumN_1 \cdot I_1 \cdot SumN_2 \cdot 0_1 \cdot I_2 \cdot 1_2 \cdot N_2 \cdot SumN_3 \cdot SumN_4 \cdot I_3$

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Data Slice for ProdN

```
( N  : Integer;
 Var   SumN, ProdN : Integer);
Var              I  : Integer
Begin
    SumN        : = 0;
    ProdN       : = 1;
    For  I      : =  1  to  N   do begin
         SumN : =    SumN   +   I
         ProdN: =   ProdN    *   I
    End;
End;
```

Data Slice for ProdN = $N_1 \cdot ProdN_1 \cdot I_1 \cdot ProdN_2 \cdot 1_1 \cdot I_2 \cdot 1_2 \cdot N_2 \cdot ProdN_3 \cdot ProdN_4 \cdot I_4$

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Data token	SumN	ProdN
N_1	1	1
$SumN_1$	1	
$ProdN_1$		1
I_1	1	1
$SumN_2$	1	
0_1	1	
$ProdN_2$		1
1_1		1
I_2	1	1
1_2	1	1
N_2	1	1
$SumN_3$	1	
$SumN_4$	1	
I_3	1	
$ProdN_3$		1
$ProdN_4$		1
I_4		1

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Super Glue

S_1	S_2	S_3	
I	I	I	Super Glue
I			
	I		
		I	
I	I	I	Super Glue
	I		
I	I		Glue
	I	I	Glue

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Functional Cohesion

- Strong functional cohesion (SFC) in this case is the same as WFC

  SFC = 5/17 = 0.204

- If we had computed only SumN or ProdN then

  SFC = 17/17 = 1

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Coupling

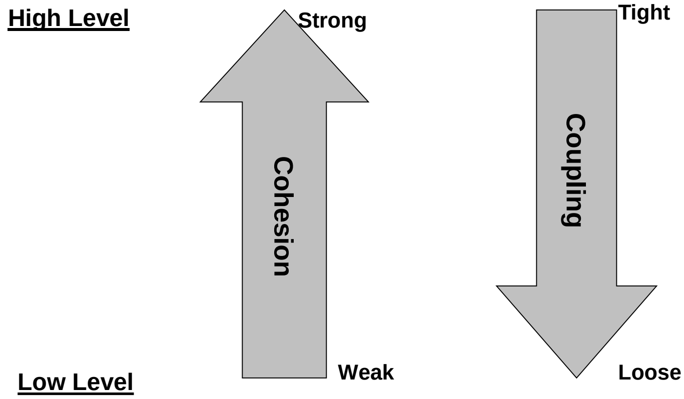
- Measure of the strength of inter-module connections
- High coupling indicates strong dependence between modules
  - Should study modules as a pair
  - Change to one module may ripple to the next
- Loose coupling indicates independent modules
  - Generally we desire loose coupling, easier to comprehend and adapt

Types of Coupling

1. Content
   – One module directly affects the workings of another
   – Occurs when a module changes another module's data
   – Generally should be avoided
2. Common
   – Two modules have shared data, e.g. global variables
3. External
   – Modules communicate through an external medium, like a file
4. Control
   – One module directs the execution of another by passing control information (e.g. via flags)
5. Stamp
   – Complete data structures or objects are passed from one module to another
6. Data
   – Only simple data is passed between modules

Modern Coupling

- Modern programming languages allow private, protected, public access
- Coupling may be modified to indicate levels of visibility, whether coupling is commutative
- Simple Interfaces generally desired
  – Weak coupling and strong cohesion
  – Communication between programmers simpler
  – Correctness easier to derive
  – Less likely that changes will propagate to other modules
  – Reusability increased
  – Comprehensibility increased



Cohesion and Coupling

Dharma (1995)

- Data and control flow coupling
  - d_i = number of input data parameters
  - c_i = number of input control parameters
  - d_o = number of output data parameters
  - c_o = number of output control parameters
- Global coupling
  - g_d = number of global variables used as data
  - g_c = number of global variables used as control
- Environmental coupling
  - w = number of modules called (fan-out)
  - r = number of modules calling the module under consideration (fan-in)

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Dharma (1995)

- Coupling metric (m_c)

  $m_c = k/M$, where $k = 1$

  $M = d_i + a^* c_i + d_o + b^* c_o + g_d + c^* g_c + w + r$

  where a=b=c=2

- The more situations encountered, the greater the coupling, and the smaller m_c
- One problem is parameters and calling counts don't guarantee the module is linked to the inner workings of other modules

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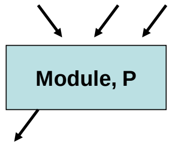
Henry-Kafura (Fan-in and Fan-out)

- **Henry and Kafura metric measures the <u>inter-modular flow,</u> which includes:**
  - **Parameter passing**
  - **Global variable access**
  - **inputs**
  - **outputs**
- **<u>Fan-in</u> : number of inter-modular flow into a program**
- **<u>Fan-out</u>: number of inter-modular flow out of a program**



Module's Complexity, Cp = (fan-in x fan-out) ^{2}

for example above: Cp = (3 + 1) ^{2} = 16

Information Hiding

- Each module has a secret that it hides from other modules
  - Secret might be inner-workings of an algorithm
  - Secret might be data structures
- By hiding the secret, changes do not permeate the module's boundary, thereby
  - Decreasing the coupling between that module and its environment
  - Increasing abstraction
  - Increasing cohesion (the secret binds the parts of a module)
- Design involves a series of decisions. For each such decision, questions are: who needs to know about these decisions? And who can be kept in the dark?

Complexity

- Complexity refers to attributes of software that affect the effort needed to construct or change a piece of software
  - Internal attributes; need not execute the software to determine their values
- Many different metrics exist to measure complexity
- Two broad classes
  - Intra-Modular attributes
  - Inter-Modular attributes

Intra-Modular Complexity

- Two types of intra-modular attributes
  - Size-Based Metrics
    - E.g. Lines of Code
      - Obvious objections but still commonly used
  - Structure-Based Metrics
    - E.g. complexity of control or data structures

Halstead's Software Science

- Size-based metric
- Uses number of operators and operands in a piece of software
  - n_1 is the number of unique operators
  - n_2 is the number of unique operands
  - N_1 is the total number of occurrences of operators
  - N_2 is the total number of occurrences of operands
- Halstead derives various entities
  - Size of Vocabulary: $n = n_1+n_2$
  - Program Length: $N = N_1+N_2$
  - Program Volume: $V = N\log_2 n$
    - Visualized as the number of bits it would take to encode the program being measured

Halstead's Software Science

- Potential Volume: $V^* = (2+n_2)\log(2+n_2)$
  - V^* is the volume for the most compact representation for the algorithm, assuming only two operators: the name of the function and a grouping operator. n_2 is minimal number of operands.
- Program Level: $L = V^*/V$
- Programming Effort: $E = V/L$
- Programming Time in Seconds: $T = E/18$
- Numbers derived empirically, also based on speed human memory processes sensory input

Halstead metrics really only measures the lexical complexity, rather than structural complexity of source code.

Software Science Example

```
procedure sort(var x:array; n: integer)
        var i,j,save:integer;
        begin
                for i:=2 to n do
                        for j:=1 to i do
                                if x[i]<x[j] then
                                begin  save:=x[i];
                                       x[i]:=x[j];
                                       x[j]:=save
                                end
        end
```

Software Science Example

Operator	#
procedure	1
sort()	1
var	2
:	3
array	1
;	6
integer	2
,	2
begin…end	2
for..do	2
if…then	1
:=	5
<	1
[]	6
n1=14	N1=35

Operand	#
x	7
n	2
i	6
j	5
save	3
2	1
1	1
n2=7	N2=25

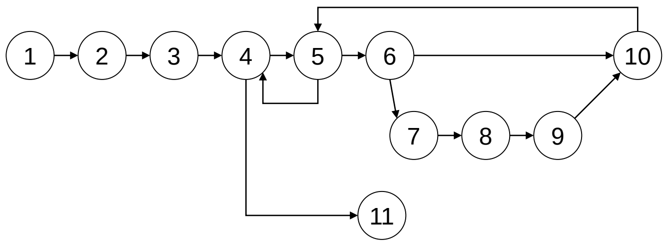
Size of vocabulary:	21
Program length:	60
Program volume:	264
Program level:	0.04
Programming effort:	6000
Estimated time:	333 seconds

Structure-Based Complexity

- McCabe's Cyclomatic Complexity
- Create a directed graph depicting the control flow of the program
  - CV = e – n + 2p
    - CV = Cyclomatic Complexity
    - e = Edges
    - n = nodes
    - p = connected components

Cyclomatic Example

For Sorting Code; numbers refer to line numbers



CV = 13 – 11 + 2*1 = 4

McCabe suggests an upper limit of 10

- **T.J. McCabe's Cyclomatic complexity metric is based on the belief that program quality is related to the complexity of the program control flow.**

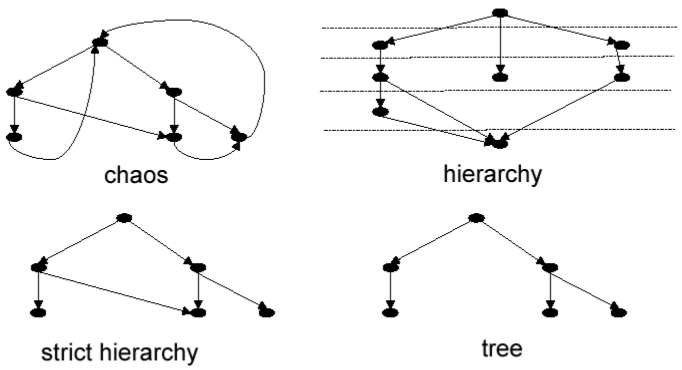
Shortcomings of Complexity Metrics

- Not context-sensitive
  - Any program with five if-statements has the same cyclomatic complexity
  - Measure only a few facts; e.g. Halstead's method doesn't consider control flow complexity
- Others?
- Minix:
  - Of the 277 modules, 34 have a CV > 10
  - Highest has 58; handles ASCII escape sequences. A review of the module was deemed "justifiably complex"; attempts to reduce complexity by splitting into modules would increase difficulty to understand and artificially reduce the CV

System Structure – Inter-Module Complexity

- The design may consist of modules and their relationships
- Can denote this in a graph; nodes are modules and edges are relationships between modules
- Types of inter-module relationships:
  – Module A contains Module B
  – Module A follows Module B
  – Module A delivers data to Module B
  – Module A uses Module B
- We are mostly interested in the last one, which manifests itself via a call graph
  – Possible shapes:
    - Chaotic
    - Directed Acyclic Graph (Hierarchy)
    - Layered Graph (Strict Hierarchy)
    - Tree

Module Hierarchies



Graph Metrics

- Metrics use:
  - Size of the graph
  - Depth
  - Width (maximum number of nodes at some level)
- A tree-like call graph is considered the best design
  - Some metrics measure the deviation from a tree; the **tree impurity** of the graph
  - Compute number of edges that must be removed from the graph's minimum spanning tree
- Other metrics
  - Complexity(M) = fanin(M)*fanout(M)
  - Fanin/Fanout = local and global data flows

Software Metrics Etiquette

- Use common sense and organizational sensitivity when interpreting metrics data.
- Provide regular feedback to the individuals and teams who have worked to collect measures and metrics.
- Don't use metrics to appraise individuals
- Work with practitioners and teams to set clear goals and metrics that will be used to achieve them.
- Never use metrics to threaten individuals or teams.
- Metrics data that indicate a problem area should not be considered "negative". These data are merely an indicator for process improvement.
- Don't obsess on a single metric to the exclusion of other important metrics.