Software Component Synthesis: Theory and Supporting Tools

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fondúireacht eolaíochta éireann

PLEAN FORBARTHA NÁISIÚNTA

Components in Engineering

Mechanical component:

- An independently specified and produced (small) part of a machine. Example: A rivet

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Component specification:

Functional: rivet size, material, etc.

Quality: tolerance, hardness

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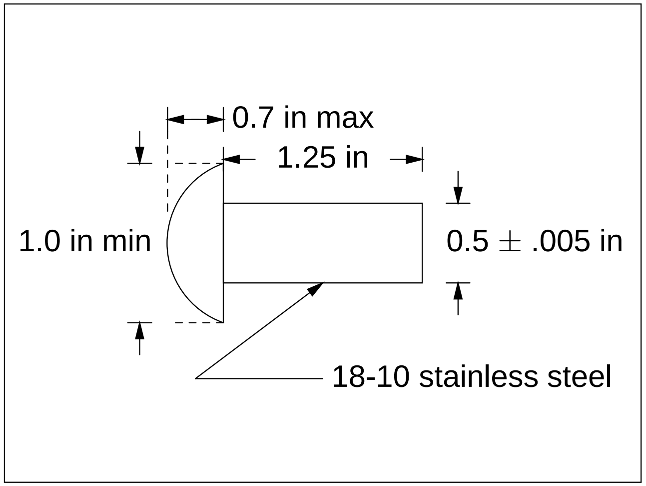
Component specification:



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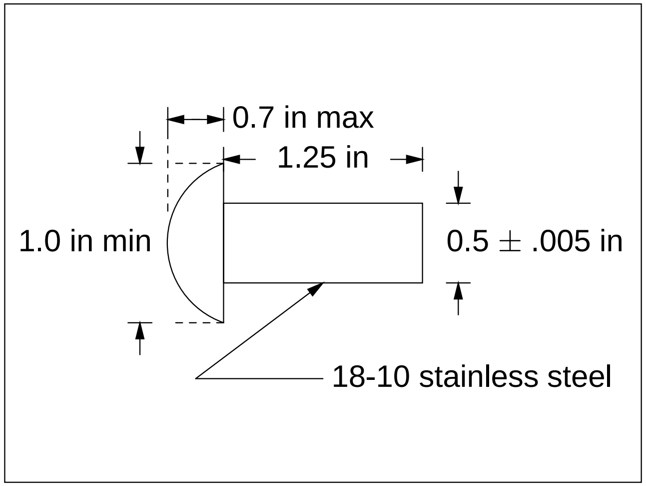

Engineering design is combining components and calculating properties of the resulting system

Component-based design spectacularly successful in electrical, mechanical engineering

Software Components? (Me too!)

- Definition (Szyperski): An executable, independently-deployable software unit with a black-box interface
- In practice: Anything from a small utility program (e.g., UNIX ‘cp’) to a large system (e.g., Adobe acrobat)
- In this research: An executable program with one floating-point input and output, no persistent internal state

Component-based Software

Component developer:

- Specify components: catalogue
- Complete access to all component details
- *No* knowledge of subsequent application

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System designer:

- Devise system structure (architecture)
- Select components from catalogue
- Calculate system properties
- *No* access to actual components

Theory from Program Proving

Specify function f and run time $T(x)$ on input x

Mathematical specifications:

- Program logic (Hoare)
- Algebraic equations (Gougen)
- Functional set theory (Mills)

Two components C_1 and C_2 in series:

$$f(x) = f_2(f_1(x))$$

$$T(x) = T_1(x) + T_2(f_1(x))$$

Practicality: Deriving T and f is difficult

Theory from Program Testing

Sample the input space to estimate f and T.

Operational-profile problem:

- Input domain is on the order of size $2^{64} \approx 10^{19}$ but only 10^5 samples are practical
- Valid sampling requires a distribution
- The distribution a component sees in a system depends on the *system* input distribution and the *system* structure, not available to the component developer

Solving the Operational-profile Problem

- Partition component input space into subdomains $D = \cup_{i=1}^{n} S_i$
- Approximate component behavior on each subdomain: $<v_1, v_2, ..., v_n> \equiv <v_i>_{i=1}^{n}$
- Profile $<w_1, w_2, ..., w_n>$ as a weighting over subdomains
  - Component developer measures $<v_i>_{i=1}^{n}$
  - System designer later applies $<w_i>_{i=1}^{n}$

    to get a system average: $\frac{1}{n}\sum_{i=1}^{n} w_i v_i$

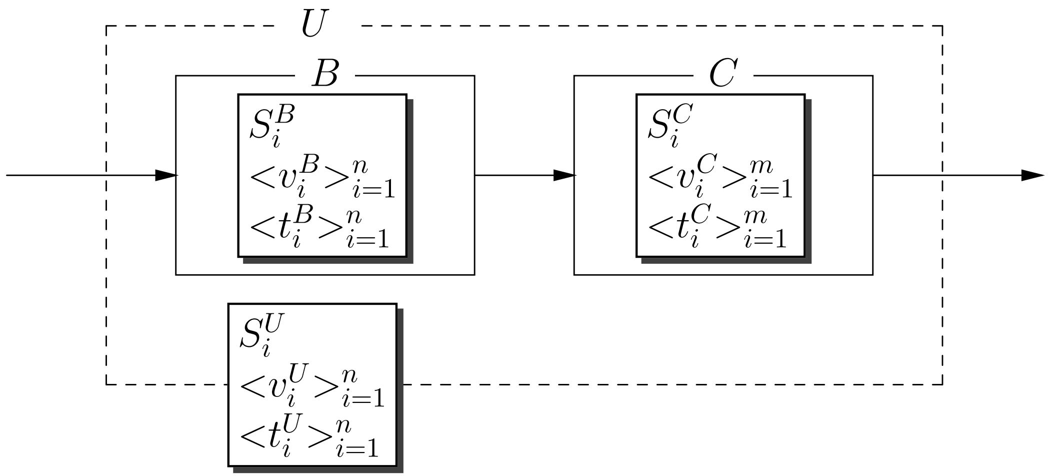
Algebra of Equivalent Components

- ‘Equivalent component’ construction rules:
  - sequence
  - conditional
  - iteration

$$\{\text{component specs}\} \xrightarrow{rule} \text{equiv-component spec}$$

- Repeatedly apply the rules to analyze a system of arbitrary complexity

Subdomain, Vector Notation



Component subdomains: $\{S_1^B, S_2^B, ..., S_n^B\}$
$\{S_1^C, S_2^C, ..., S_m^C\}$

Functional vectors: $<v_1^B, v_2^B, ..., v_n^B>$
$<v_1^C, v_2^C, ..., v_m^C>$ $\Rightarrow <v_1^U, v_2^U, ...v_n^U>$

Run-time vectors: $<t_1^B, t_2^B, ..., t_n^B>$
$<t_1^C, t_2^C, ..., t_m^C>$ $\Rightarrow <t_1^U, t_2^U, ...t_n^U>$

Sequence rule: $C_1; C_2$

Subdomains: $S_i^U = S_i^{C_1}$

Suppose $v_i^{C_1} \in S_j^{C_2}$. Then:

Functional values: $v_i^U = v_j^{C_2}$

Run-time values: $t_i^U = t_i^{C_1} + t_j^{C_2}$

Conditional: `if` B `then` C_1 `else` C_2 `fi`

Let: $D_T = \{x | B(x)\}$
$D_F = \{x | \neg B(x)\}$

On subdomains $D_T \cap S_i^{C_1}$:

$$v_k^U = v_i^{C_1}$$
$$t_k^U = t_p^B + t_i^{C_1}$$

On subdomains $D_F \cap S_j^{C_2}$:

$$v_k^U = v_j^{C_2}$$
$$t_k^U = t_p^B + t_j^{C_2}$$

Iteration rule: `while` B `do` C `od`

- Unwind to:

  $$\texttt{if}\ B\ \texttt{then}\ C\ \texttt{else}\ I\ \texttt{fi};\ \texttt{while}\ B\ \texttt{do}\ C\ \texttt{od}$$

  where I is the component computing identity with zero run time
- Repeat until residual loop disappears in each subdomain
- Use conditional and sequence rules

Piecewise-linear Approximation

Replace the vector constants v_i, t_i with pairs

(*slope, intercept*)$_i$

of the best-fit line over the subdomain

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  - Exact representation of the identity component I

Piecewise-linear Approximation

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- Advantages:
  - Better subdomains for sequences
  - Exact representation of the identity component I
- Disadvantage: Can't be used with non-numeric data types

Ideal Supporting Tools

Components are measured to drive a computer-aided design (CAD) tool that does system-design calculations

Systems are designed using a components catalogue, without any access to component code and without constructing or executing any system code

Tools for Component Developers

Create catalog entry (specification) from:

- Subdomain list
- Component code

```
1.bin
0 20 13
20 40 13
40 61 13
61 70 13
70 83 13
83 100 13
```

```
#! /usr/bin/perl
$x = <STDIN>;
$y = (($x**2)/10)*exp(-($x**2)/1500) + 35;
if ($x < 61) {
  $t = 5 + 2*sin($x/5);
}
elsif ($x >= 61 && $x < 83) {
  $t = 12 + 3*sin($x/3);
}
else {
  $t = 13;
}
$t = $t*.2;
print STDERR $t,"\n";
print $y,"\n";
```

Tools for Component Developers

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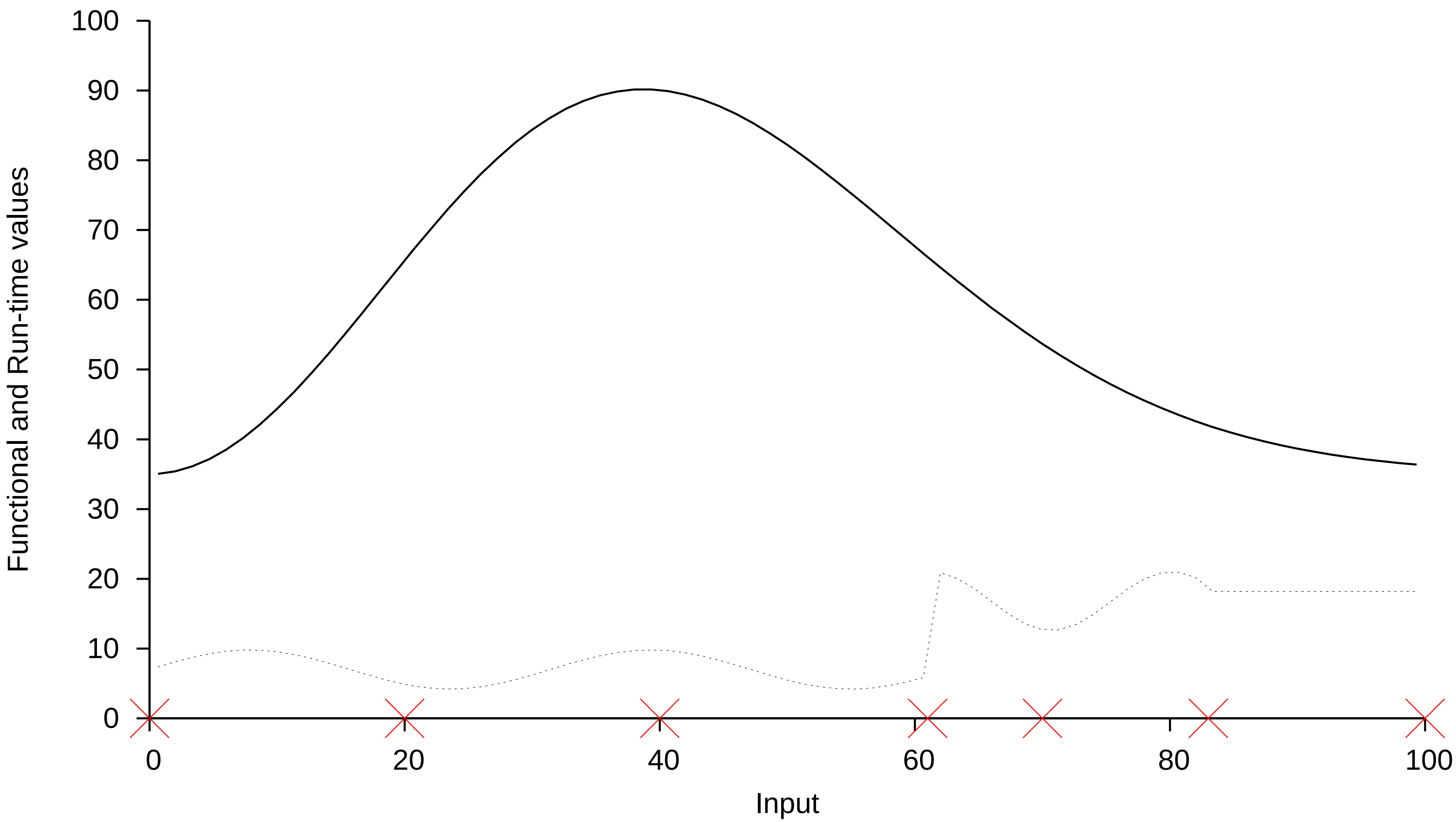
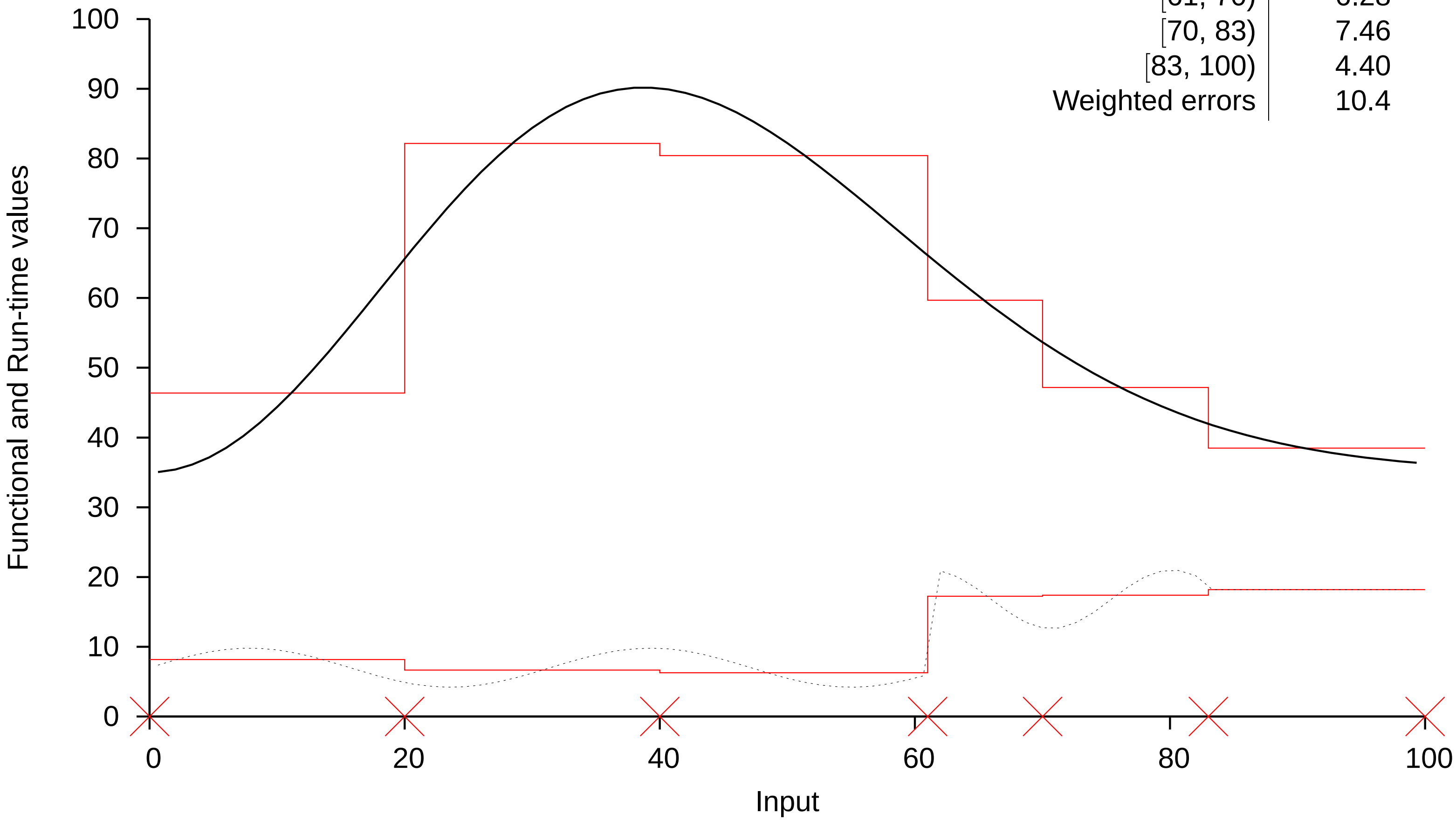


Approximating Component Behavior

Step-function approximation

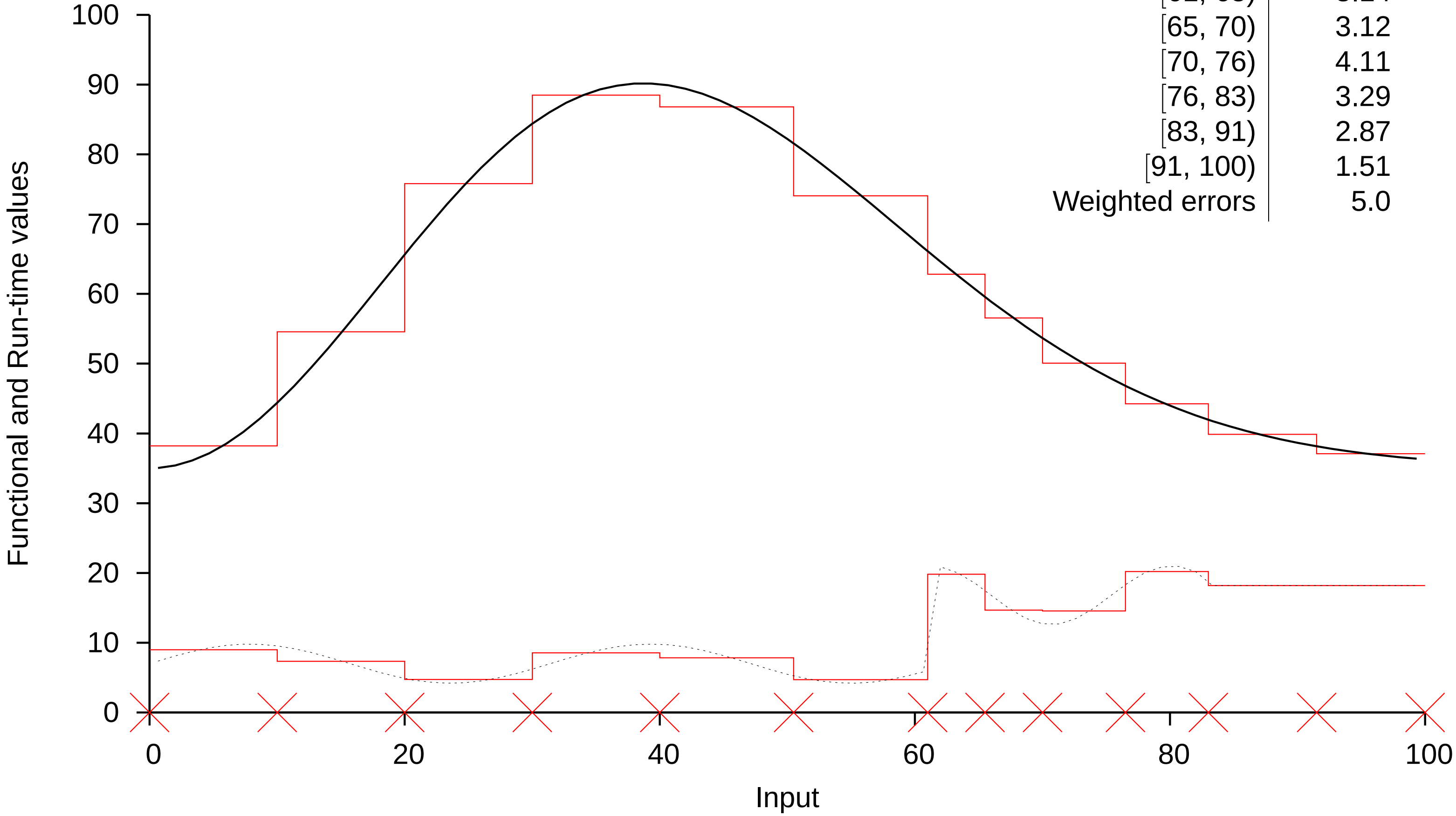
Subdomain	Root-mean-square % errors Function	Run time
[0, 20)	21.28	18.38
[20, 40)	9.52	32.97
[40, 61)	9.49	31.37
[61, 70)	6.28	17.32
[70, 83)	7.46	18.86
[83, 100)	4.40	0.00
Weighted errors	10.4	20.9



Approximating Component Behavior

Step-function approximation

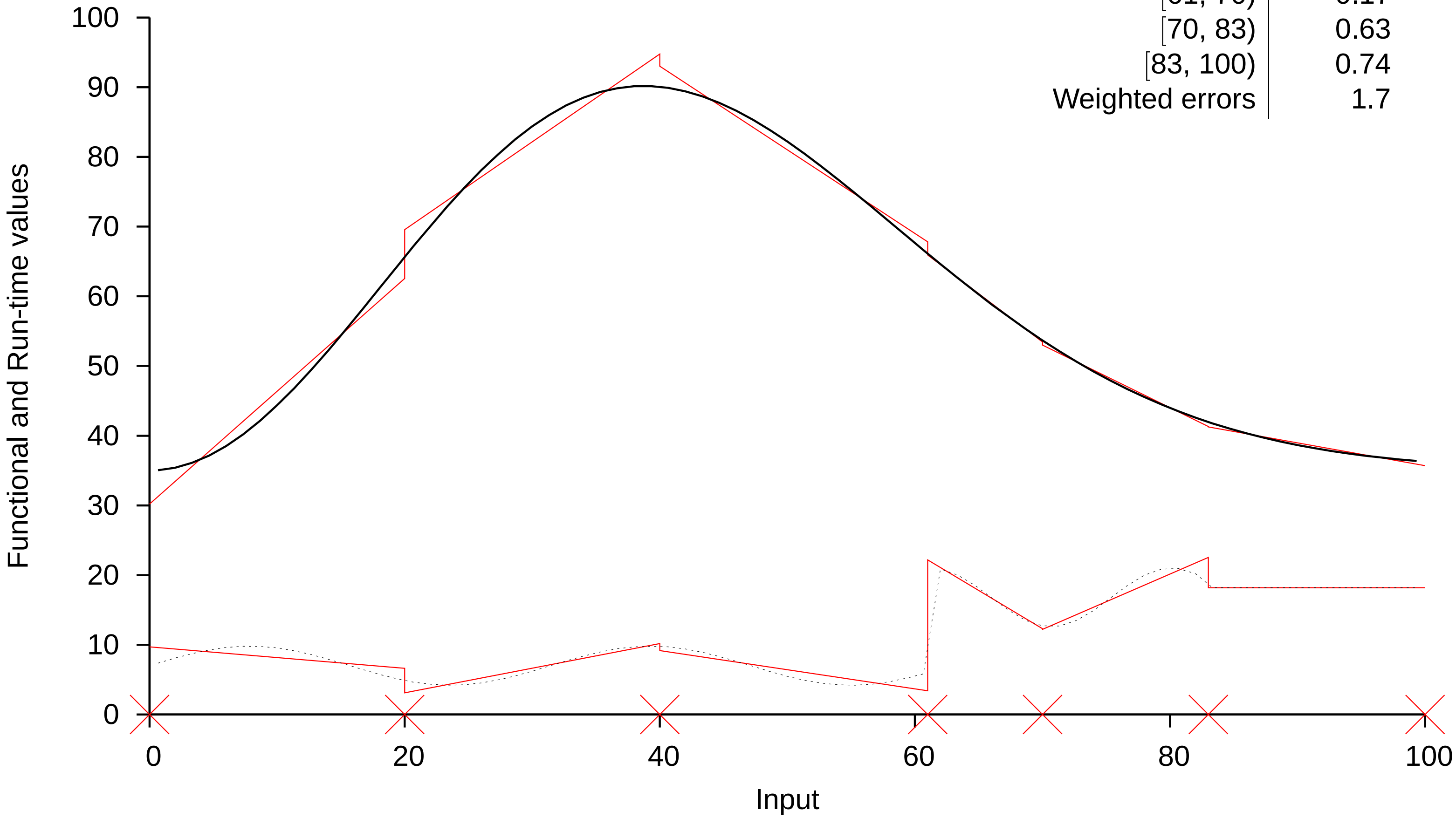
Subdomain	Root-mean-square % errors Function	Run time
[0, 10)	7.65	9.87
[10, 20)	11.84	20.53
[20, 30)	7.50	12.16
[30, 40)	2.03	13.74
[40, 50)	3.03	18.84
[50, 61)	6.31	10.51
[61, 65)	3.14	5.72
[65, 70)	3.12	10.18
[70, 76)	4.11	12.97
[76, 83)	3.29	3.70
[83, 91)	2.87	0.00
[91, 100)	1.51	0.00
Weighted errors	5.0	10.5



Approximating Component Behavior

Piecewise-linear approximation

Subdomain	Root-mean-square % errors Function	Run time
[0, 20)	3.87	13.97
[20, 40)	2.37	8.17
[40, 61)	1.30	14.55
[61, 70)	0.17	2.05
[70, 83)	0.63	6.07
[83, 100)	0.74	0.00
Weighted errors	1.7	8.5



Tools for System Designers

(CAD) Synthesize Equivalent component from:

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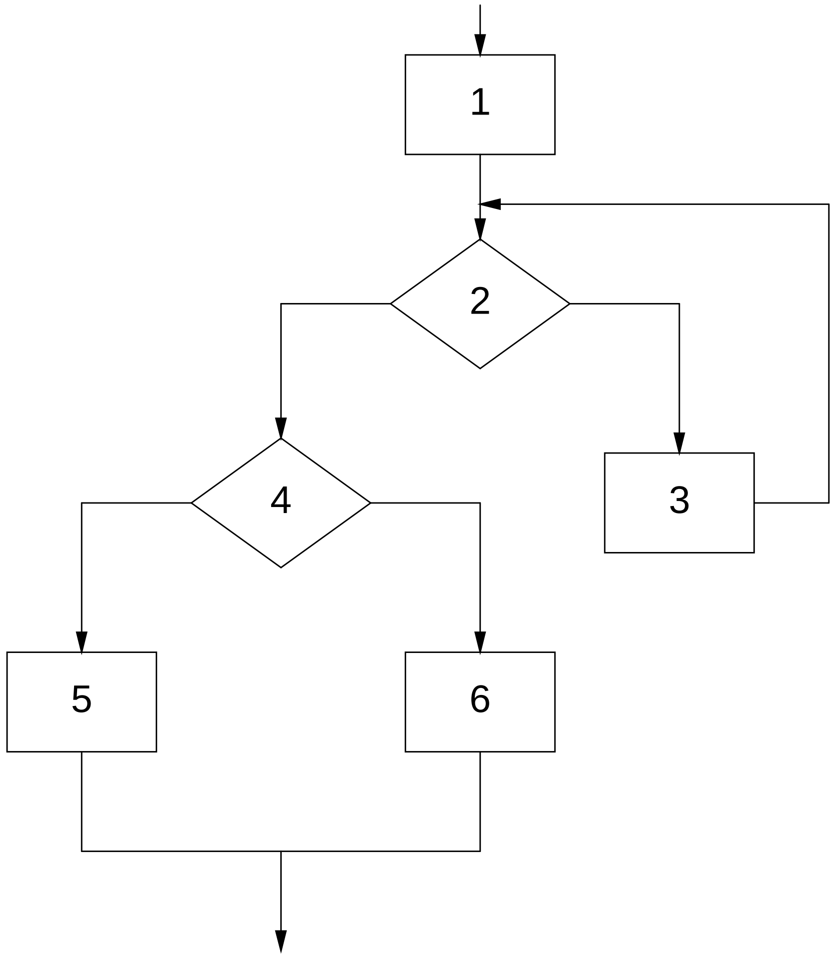

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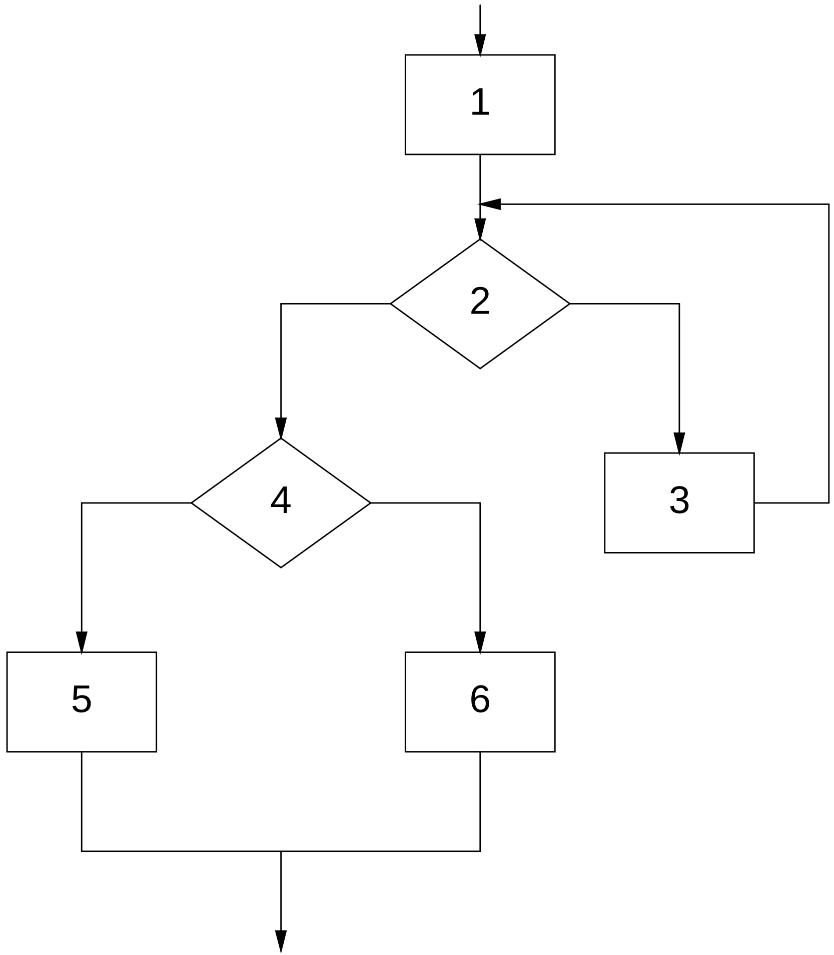



```
1 2 3 L S 4 5 6 C S
1.ccf
2.ccf
3.ccf
4.ccf
5.ccf
6.ccf
```

‘Validation’ Experiments

- Tool/theory debugging
- Creation of artificial components
- To be investigated:
  - Accuracy vs. subdomain size
  - Step-function vs. piecewise-linear approximation
  - Choice of subdomains

Artificial Components

Monitoring behavior in experiments (UNIX)
1. Time component externally

```
#! /bin/tcsh shell script
# get time in $Elapsed0 variable

perl ComPonent
# execute code, output to stdout

# get time in $Elapsed1
# compute $Elapsed = $Elapsed1 - $Elapsed0

echo $Elapsed > /dev/stderr # send time to stderr
```

Artificial Components

Monitoring behavior in experiments (UNIX)
2. Wrap component to time itself

```
#! /usr/bin/perl
# call UNIX timer function

# code for ComPonent here:
while ($LongTime) { ... } # runs 200 ms
print "99\n"; #output to stdout

# call UNIX timer function
$Diff = ...; # subtract times
print STDERR "$Diff\n"; # time to stderr
```

Artificial Components

Monitoring behavior in experiments (UNIX)
3. Fake the actual behavior

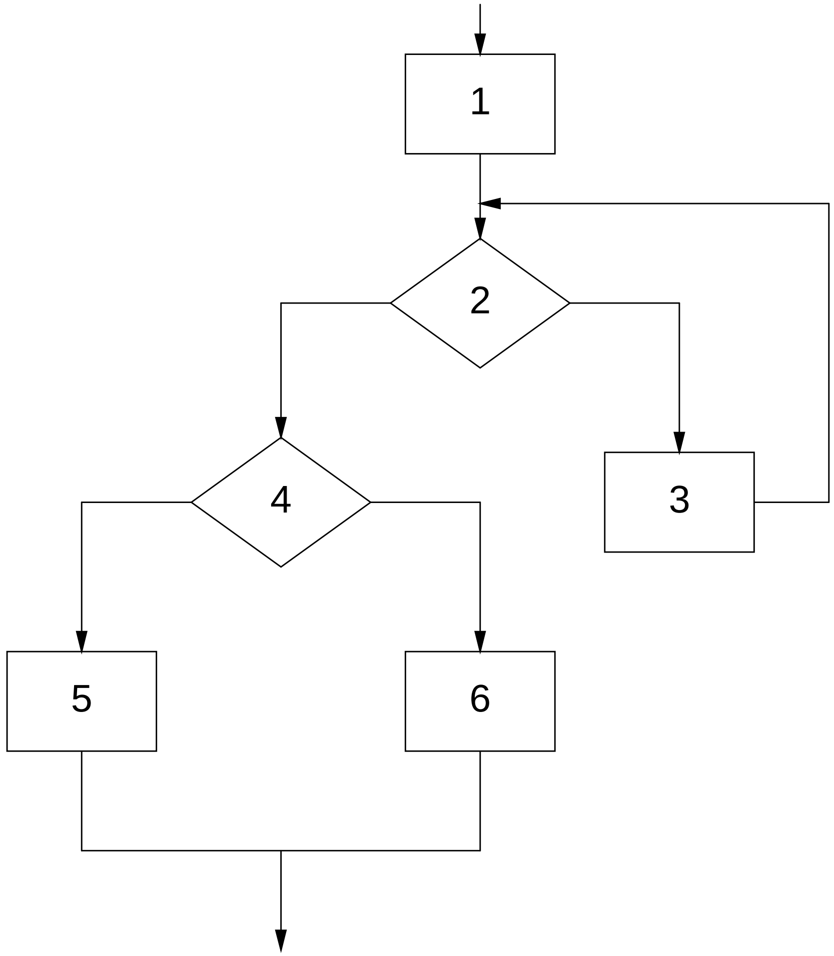
```
#! /usr/bin/perl
print "99\n"; #output to stdout
print STDERR "200\n"; # time to stderr
```

Artificial Components

Monitoring behavior in experiments (UNIX)

- Can't tell the difference!
- Fake is *much* faster
- No operating-system variability
- Measure and replace real components with fakes

Case-study System and Components



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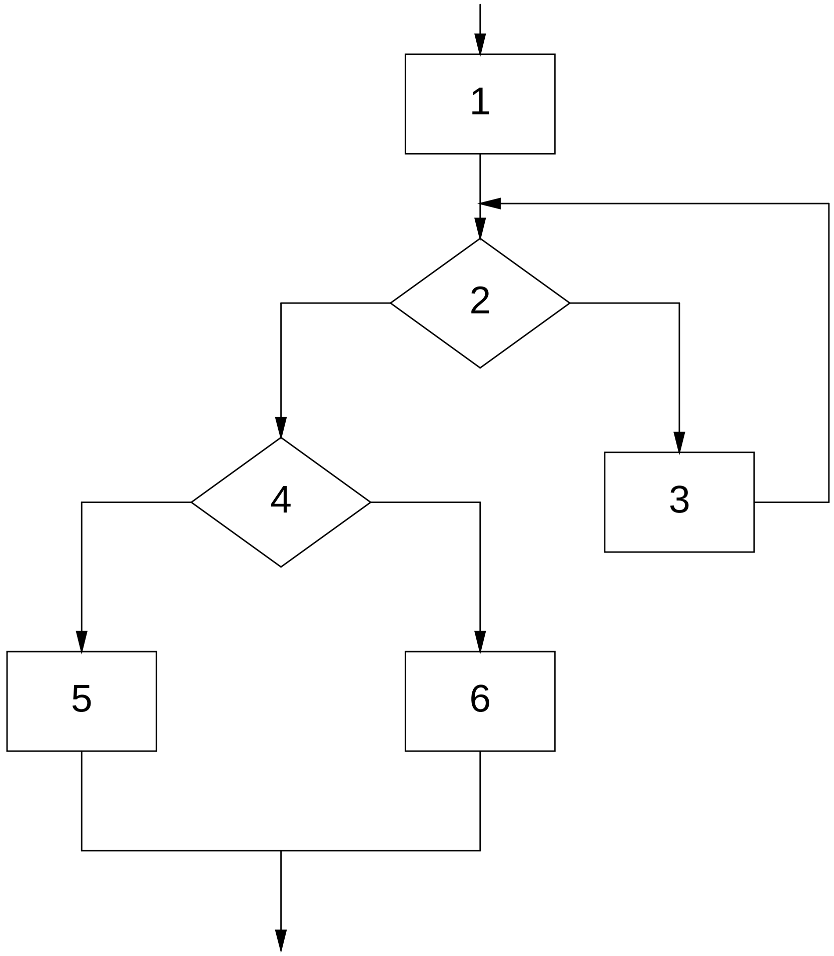
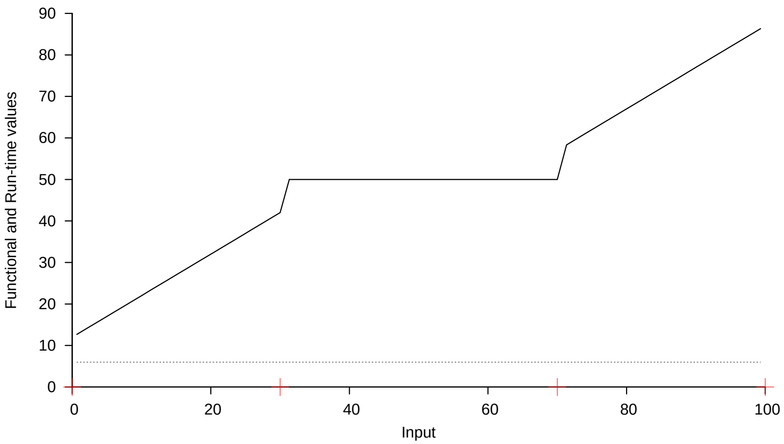


Comp	Function $y = f(x)$
1	$y = \frac{1}{10}x^2e^{-x^2/1500} + 35$
2	*false* $30 \leq x < 70$
3	(see graph)
4	*true* $x \geq 50$
5	$y = \begin{cases} 90 - 2.5x, & x < 30 \\ 15 + 1.1(x - 30), & x \geq 30 \end{cases}$
6	(same as 1)



CAD Tool Execution

```
Beginning system:  Polish 1 2 3 L S 4 5 6 C S
Using piecewise-linear approximation

Loop:  WHILE 2.bin DO 3.bin OD -> theory1
  Conditional:  IF 2.bin THEN 3.bin ELSE  FI ->
                once.ccf -> again.ccf
  (again.ccf stripped of false subdomains -- 2 true)
  Series: again.ccf; once.ccf -> another.ccf ->
          again.ccf (2 still true)
  Series: again.ccf; once.ccf -> another.ccf ->
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  Series: again.ccf; once.ccf -> another.ccf -> again.ccf

Series: 1.bin;theory1 -> theory2

Conditional:  IF 4.bin THEN 5.bin ELSE 1.bin FI -> theory3

Series: theory2;theory3 -> theory4
```
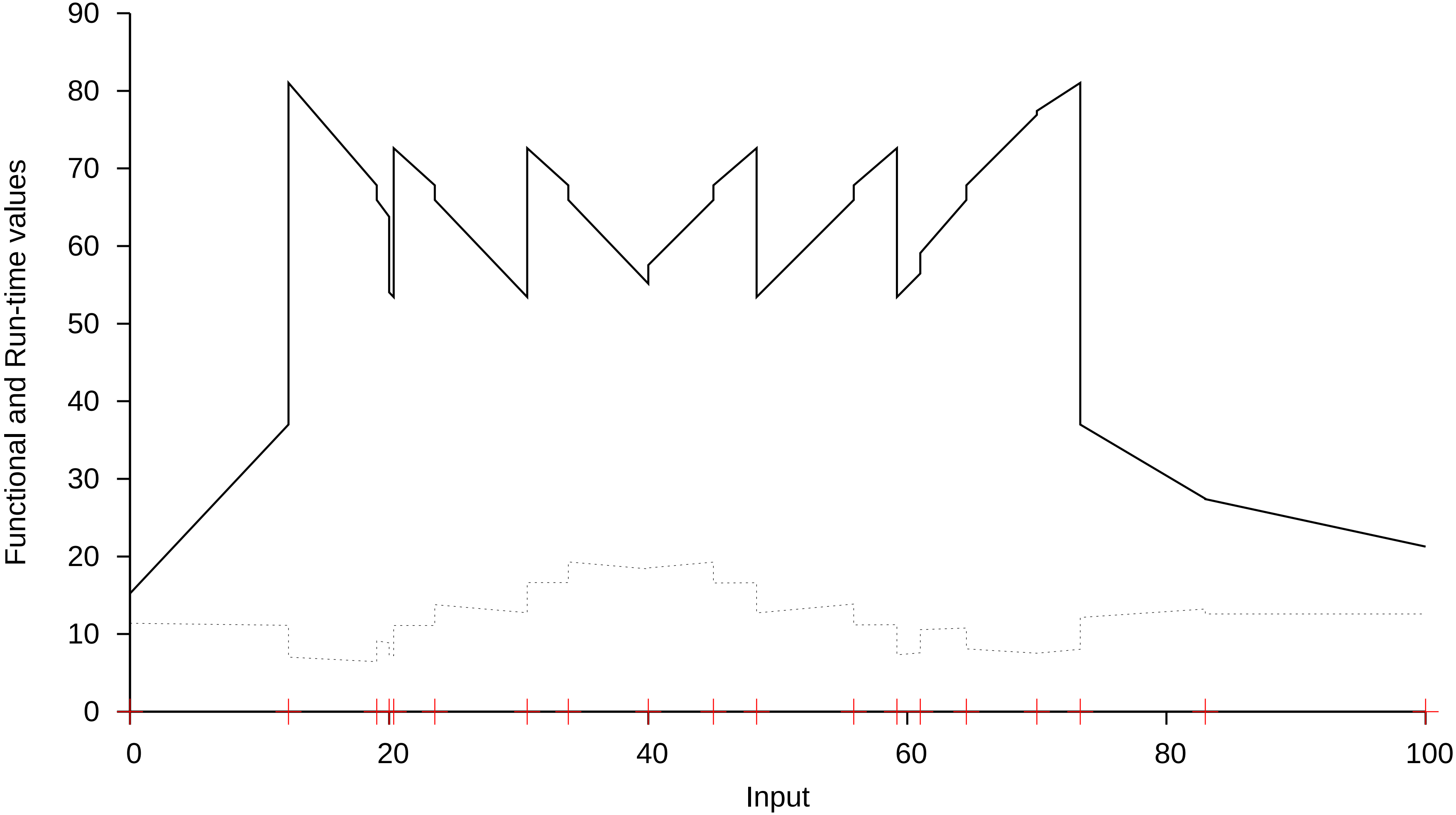

CAD Tool Execution

Subdomain	Function	Run time
[0.000,12.239)	26.11	11.25
[12.239,19.039)	74.43	6.74
[19.039,20.000)	64.85	9.01
[20.000,20.351)	53.74	7.24
[20.351,23.525)	70.23	11.11
[23.525,30.666)	59.68	13.27
[30.666,33.840)	70.23	16.63
[33.840,40.000)	60.54	18.86
[40.000,45.026)	61.74	18.91
[45.026,48.359)	70.23	16.61
[48.359,55.857)	59.68	13.30
[55.857,59.189)	70.23	11.19
[59.189,61.000)	54.94	7.45
[61.000,64.551)	62.51	10.67
[64.551,70.000)	72.37	7.82
[70.000,73.345)	79.22	7.79
[73.345,83.000)	32.22	12.67
[83.000,100.000)	24.32	12.60

CAD Tool Execution



Subdomains and Accuracy

Successively halve subdomains:

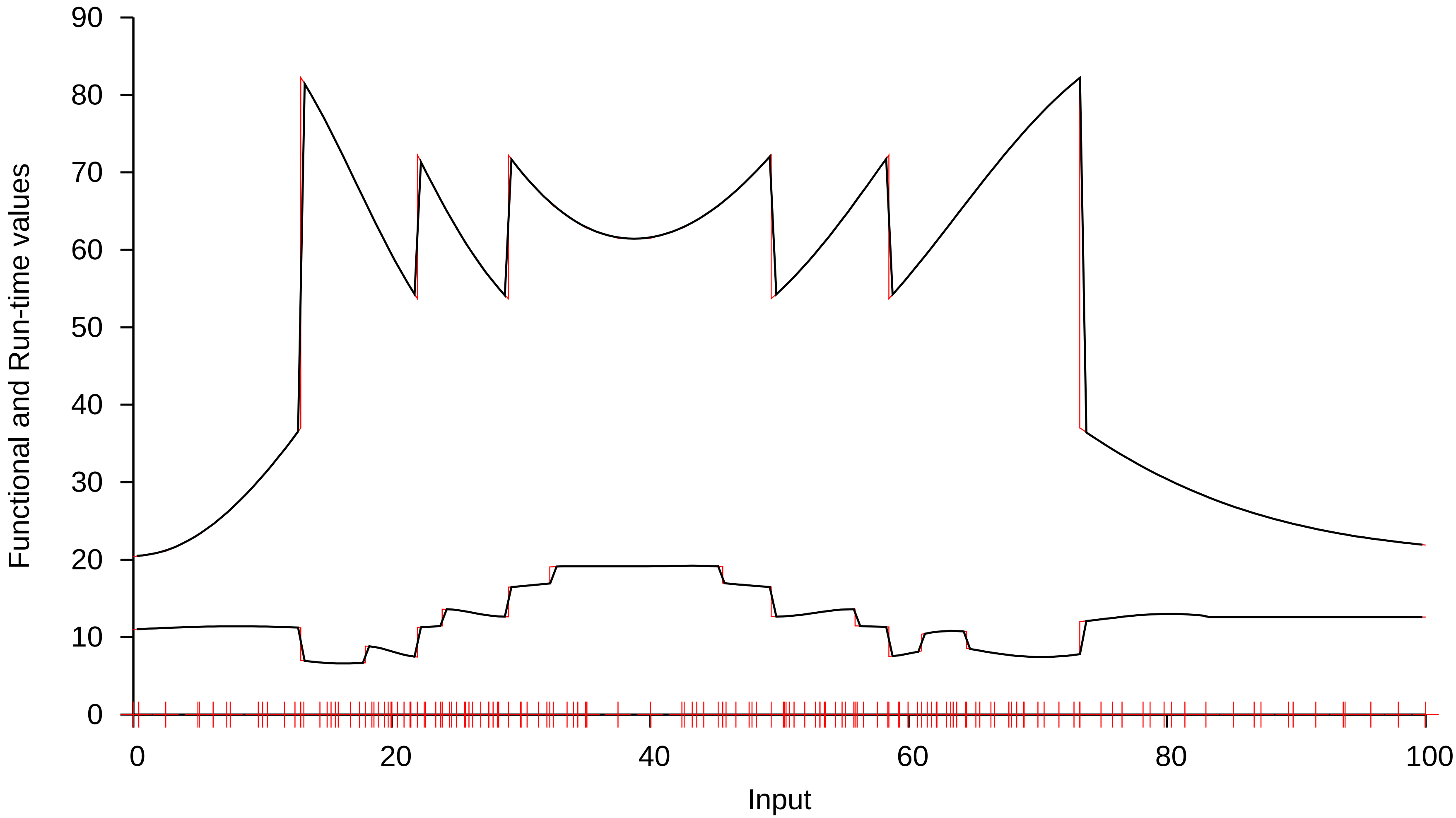
Step-function Approximation

Piecewise-linear Approximation

Subd count	Functional % error Overall	Max	Mean	> 5	Run-time % error Overall	Max	Mean	> 5
6	– ABORTED –							
12	22.13	50.21	16.59	6	9.37	21.39	7.32	5
18	5.16	12.96	3.85	6	3.56	18.87	4.49	7
24	9.69	24.61	7.86	13	8.05	40.37	6.27	8
32	0.70	21.35	1.65	3	0.40	15.71	1.49	3
48	8.47	19.01	6.13	24	3.22	17.03	2.22	7
76	0.52	55.01	0.97	2	0.55	53.55	1.00	2
96	4.42	28.85	2.82	20	1.20	18.42	0.93	5
152	0.04	55.00	0.40	1	0.02	54.02	0.41	1
192	1.40	25.01	1.55	6	0.50	15.56	0.58	9
384	0.64	34.43	0.79	5	0.09	21.73	0.32	8
768	0.69	30.46	0.42	5	0.50	27.24	0.19	8

Subdomain Boundary Problems

Even small subdomains miss discontinuities



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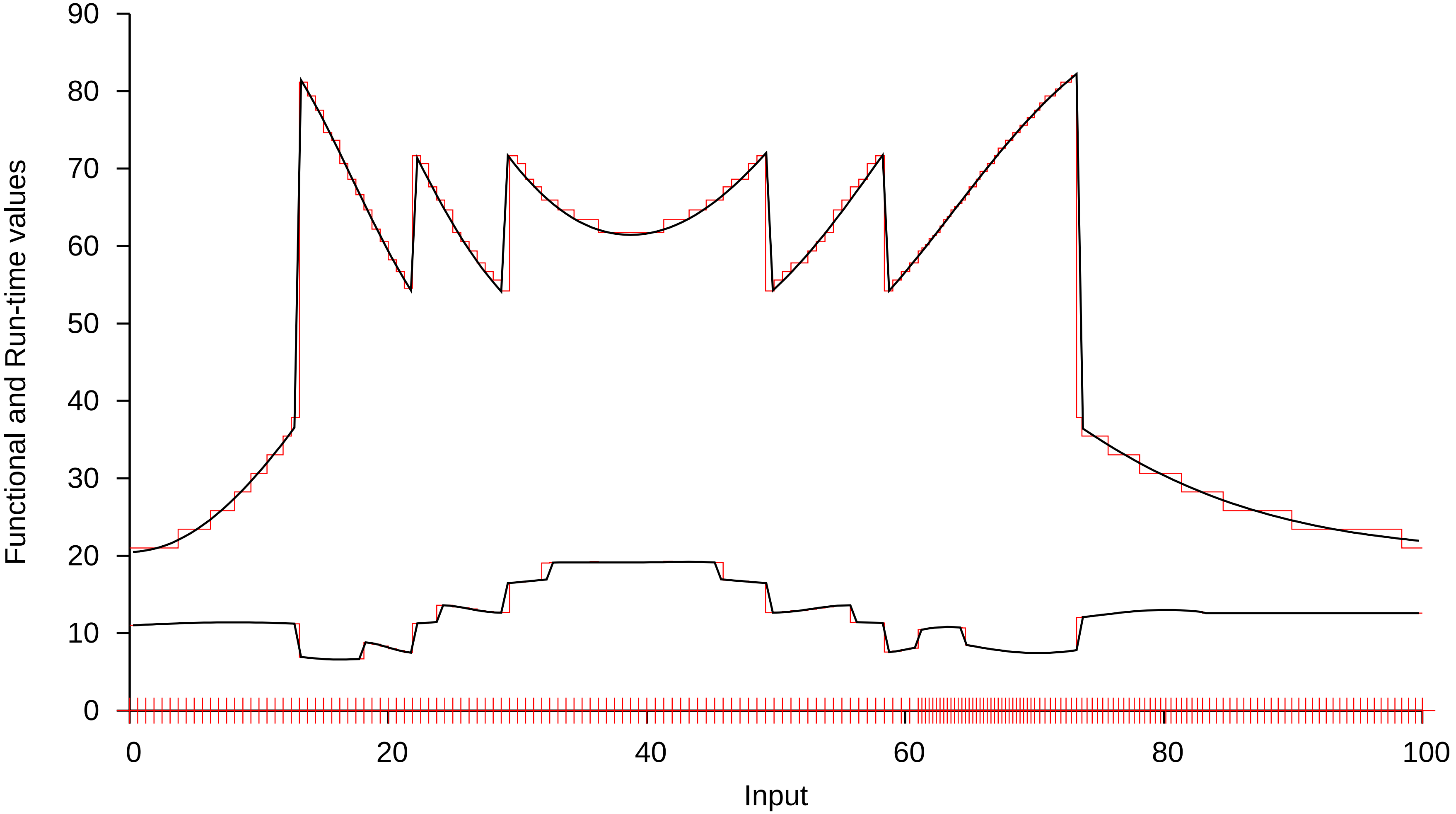

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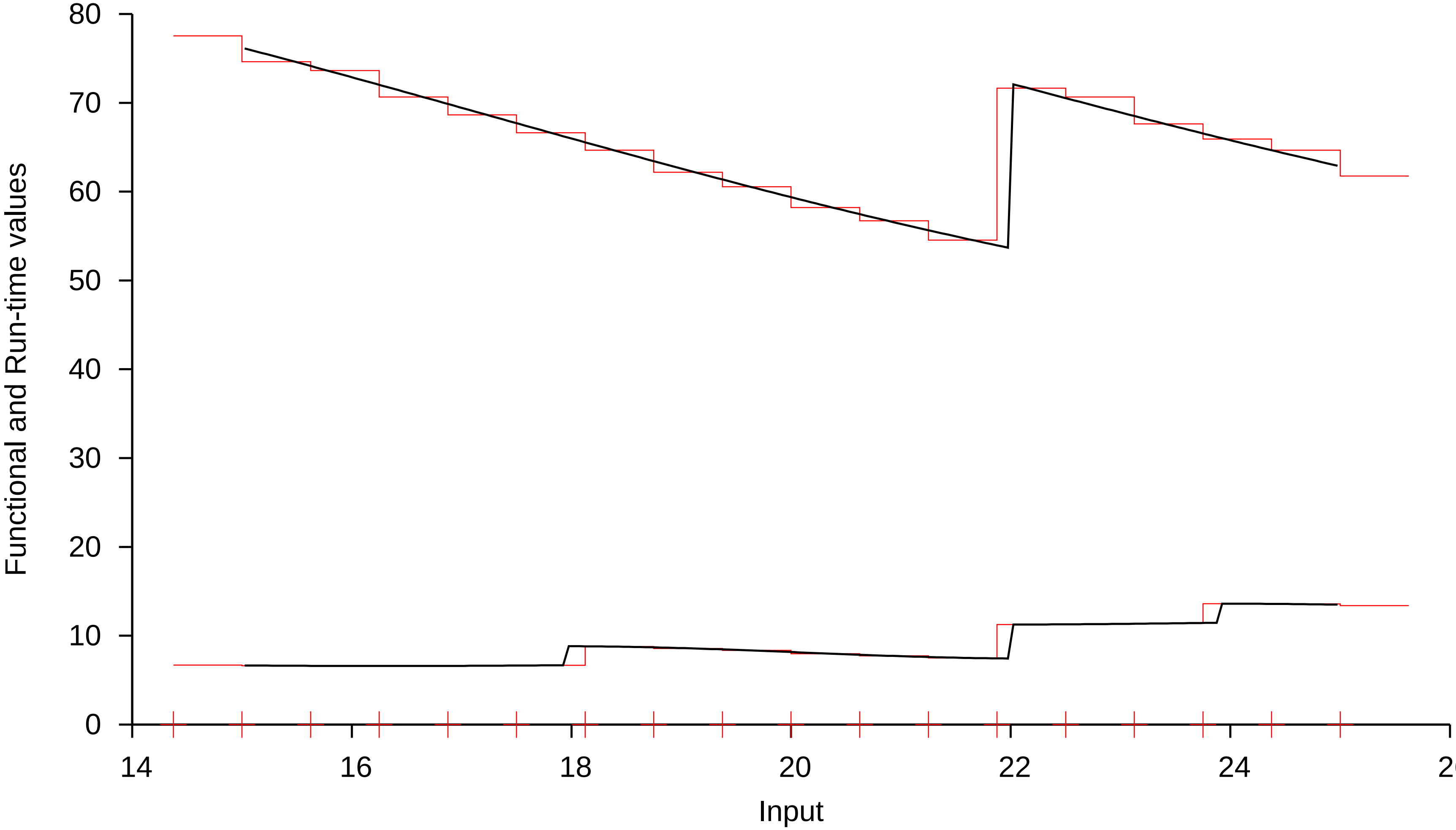

Open Problems

- Error prediction
  - Rms approximation error predictive?
  - Functions always badly behaved
- Components retaining state
  - Most real components have persistent state
  - State is not just an extra input variable

QUESTIONS? COMMENTS?