Design for Maintainability
Model-Based Diagnostics of a NASA Satellite Power System

Peter Bunus, Olle Isaksson
petbu@ida.liu.se

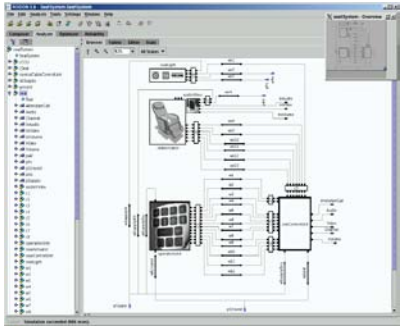

"What do you do when you're 100,000,000 miles from home and can't find a good mechanic?"
Dr. Scott J. Horowitz, NASA
The Annual Reliability and Maintainability Symposium
2007 Keynote Speech

Definition of Diagnosis

- As a subfield in artificial intelligence, **Diagnosis** is concerned with the development of algorithms and techniques that are able to determine whether the behavior of a system is correct. If the system is not functioning correctly, the algorithm should be able to determine, as accurately as possible, which part of the system is failing, and which kind of fault it is facing. The computation is based on *observations*, which provide information on the current behavior.

Model-Based Diagnosis Principles

Actual system
Passenger seat system



Model of the passenger seat system

Corrections repair actions

Observations

Observed behavior

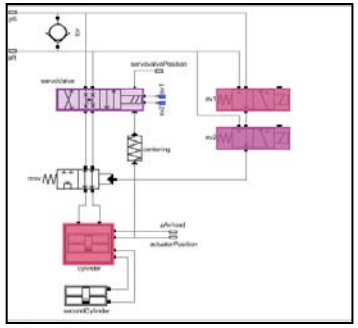
Diagnosis

Diagnostic Reasoner

Predicted behavior

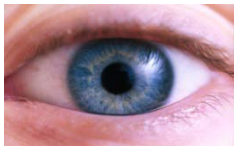
Simulation

The Diagnostic Problem



Design
Structural
Description

*V=i*R*
Domain Knowledge
Component



Measurements/
Observations

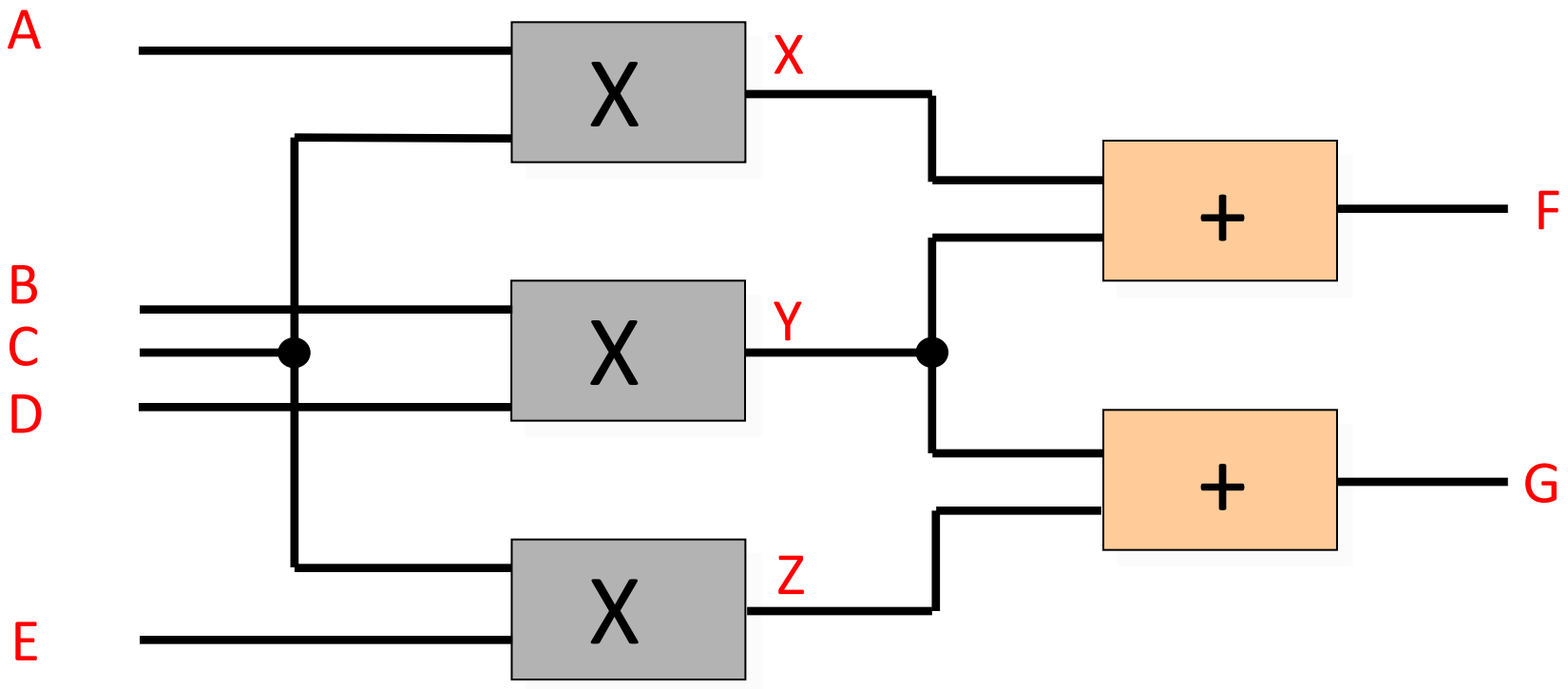
X=6V

Diagnostic
Reasoner

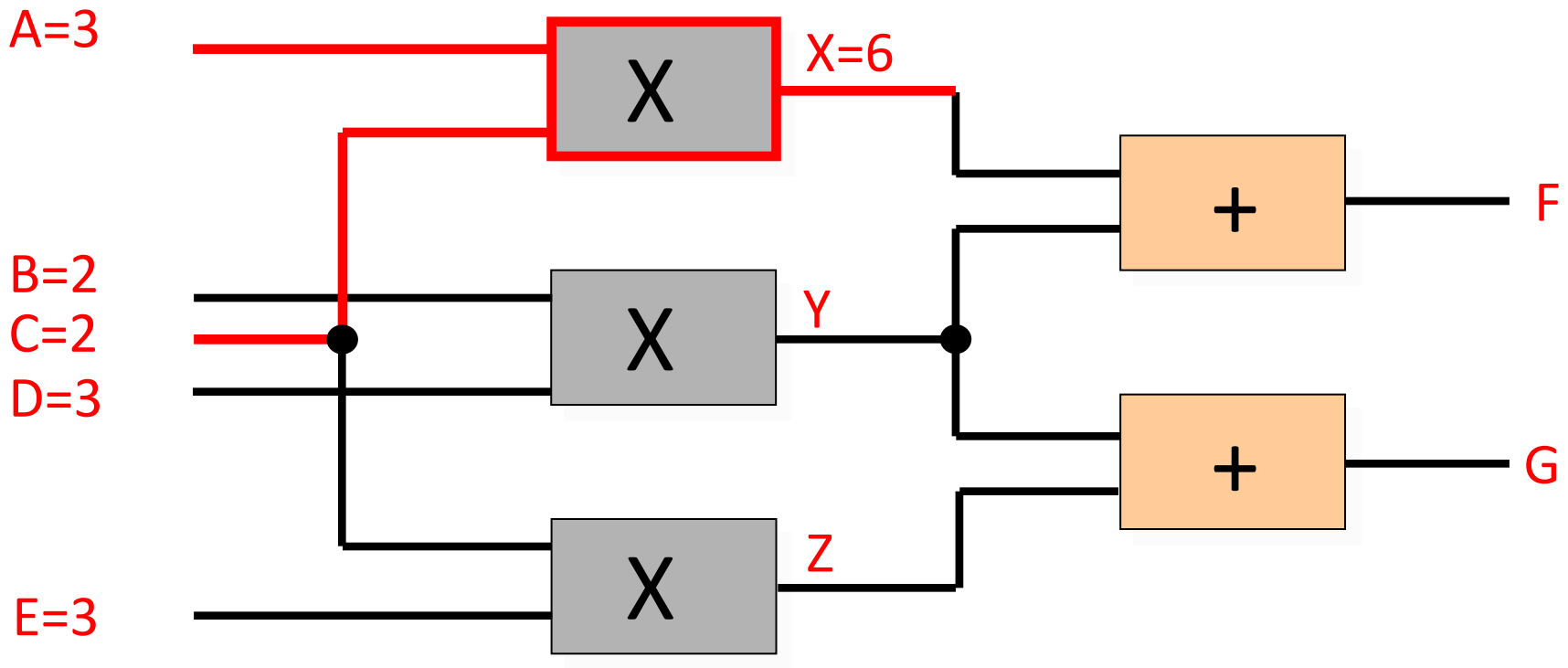
Diagnosis
Repair Actions

Replace servoValve

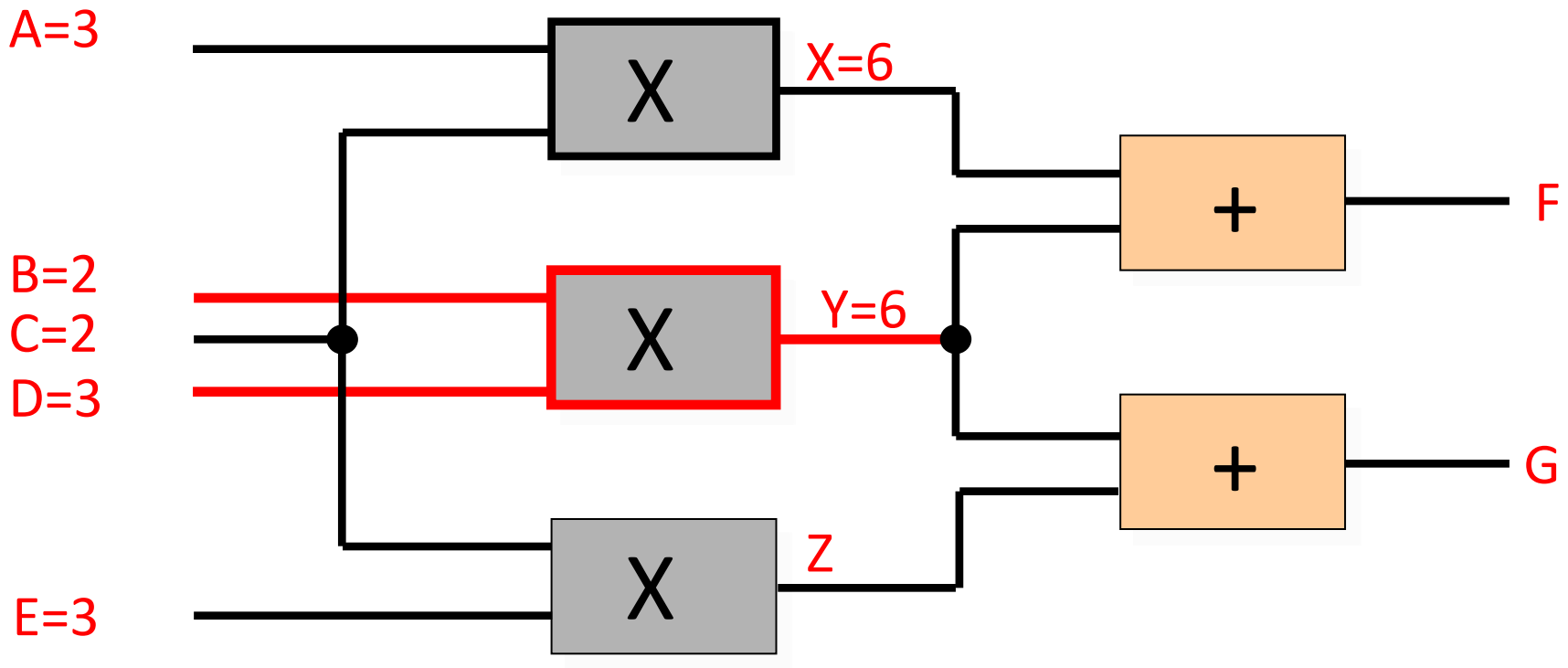
Multiplier-Adder Example



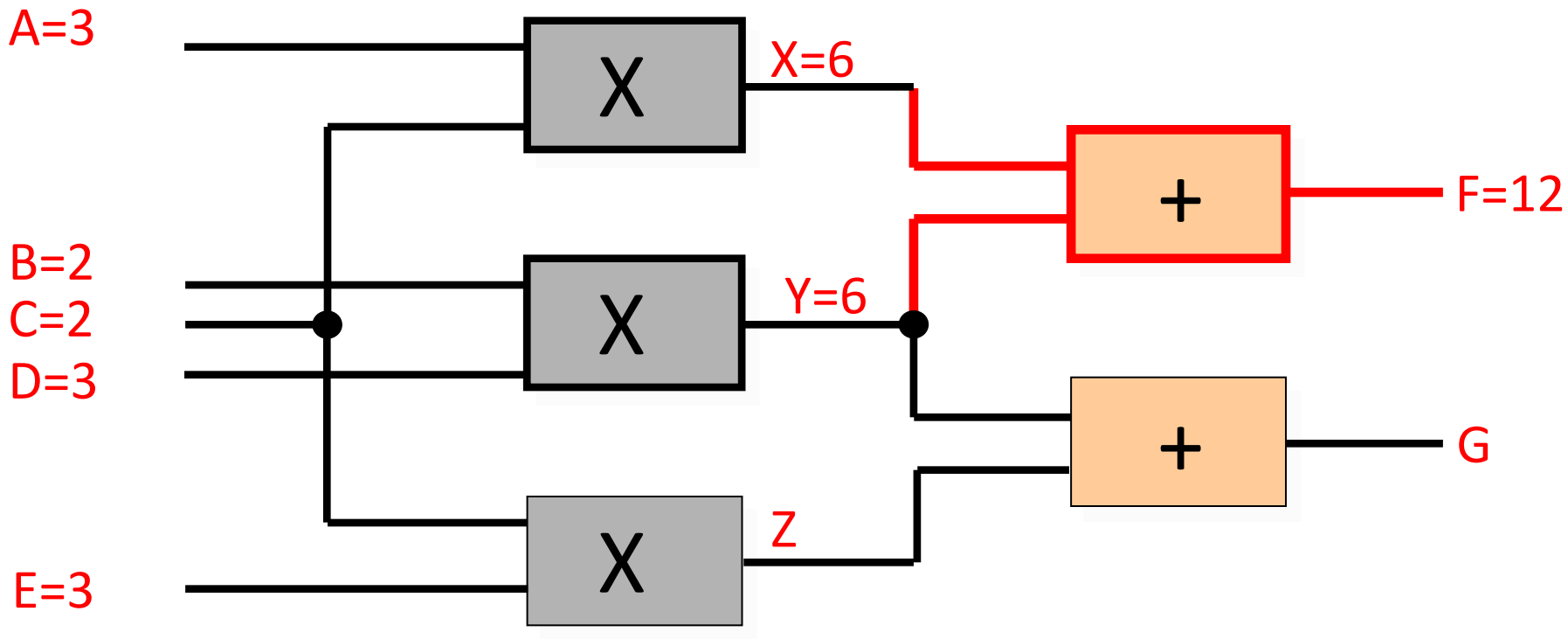
Multiplier-Adder Example



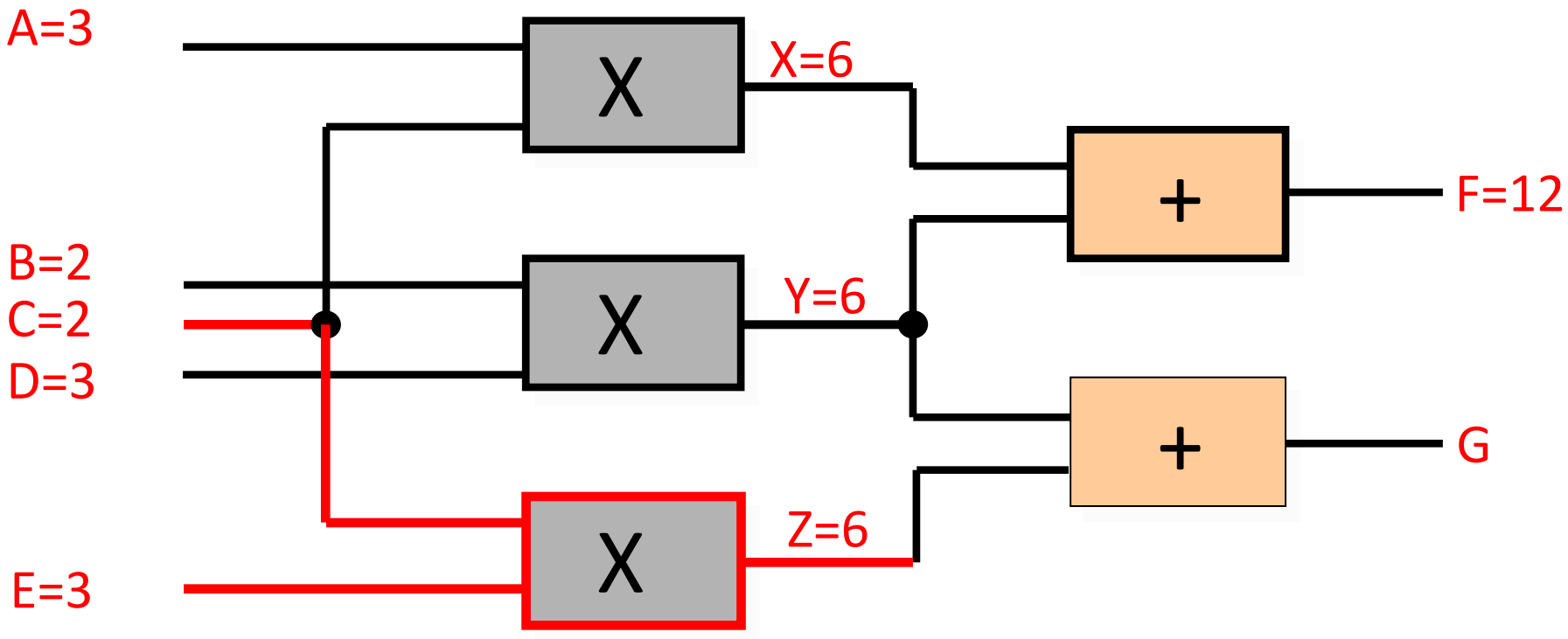
Multiplier-Adder Example



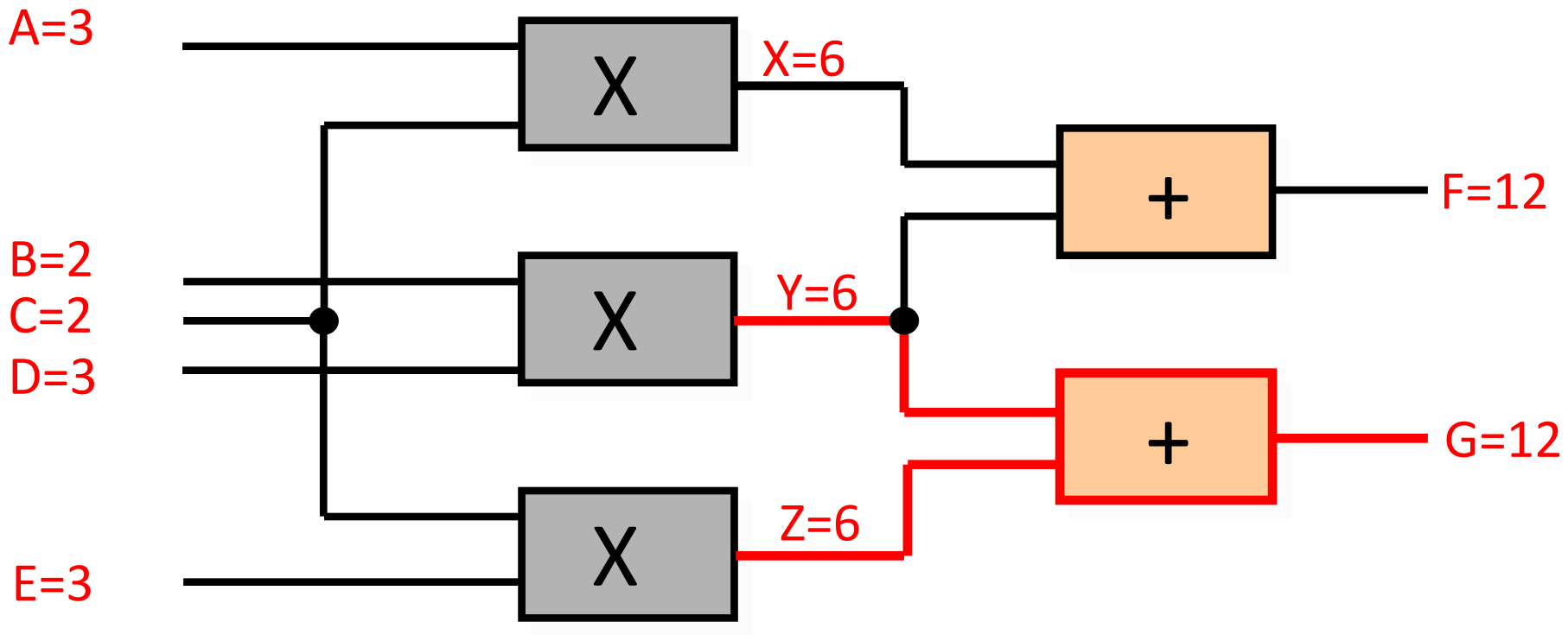
Multiplier-Adder Example



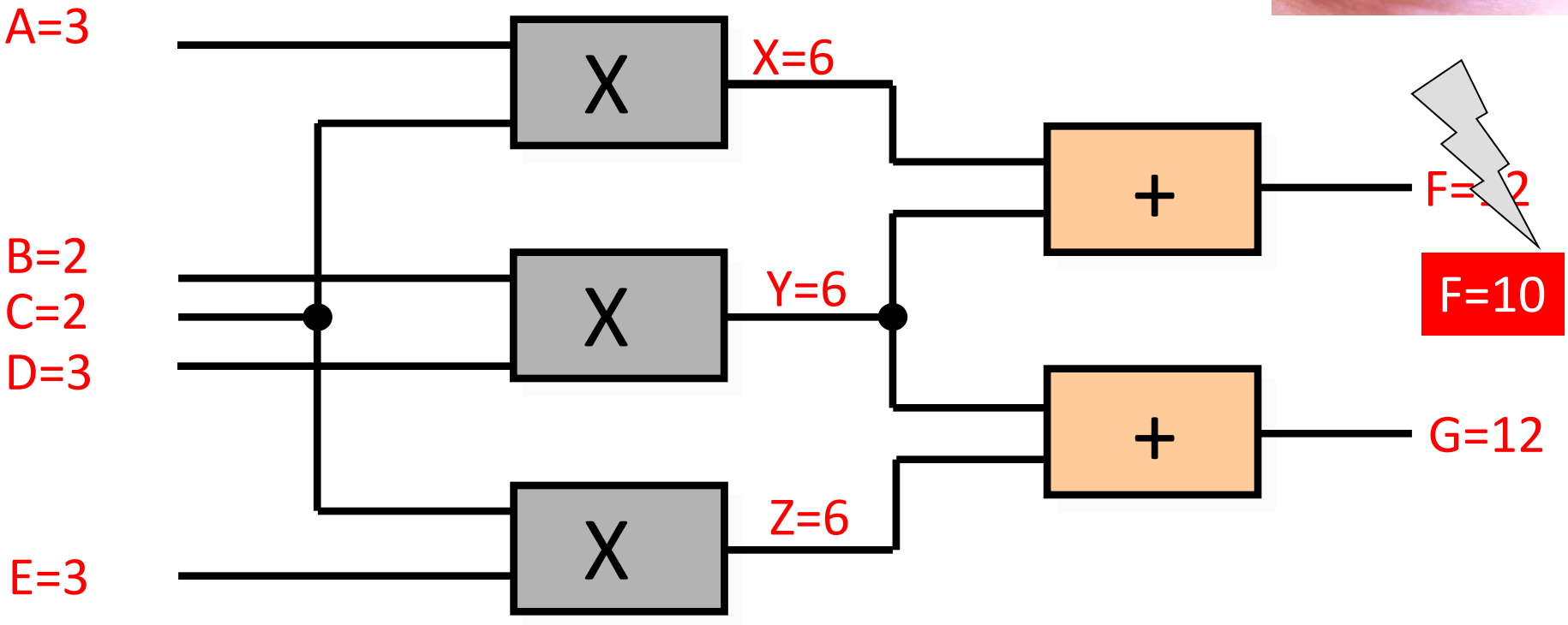
Multiplier-Adder Example



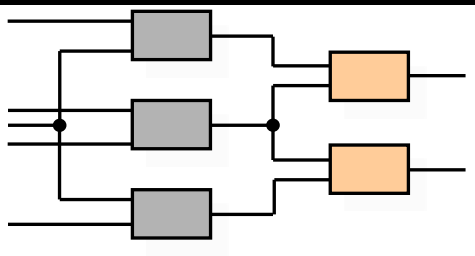
Multiplier-Adder Example



Adding Observations



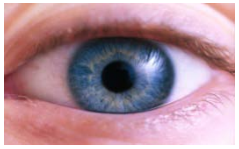
The Diagnostics Problem



Design
Structural
Description

adder -> out=in1+in2
*mult -> out=int1*int2*

Domain Knowledge
Component



Observations

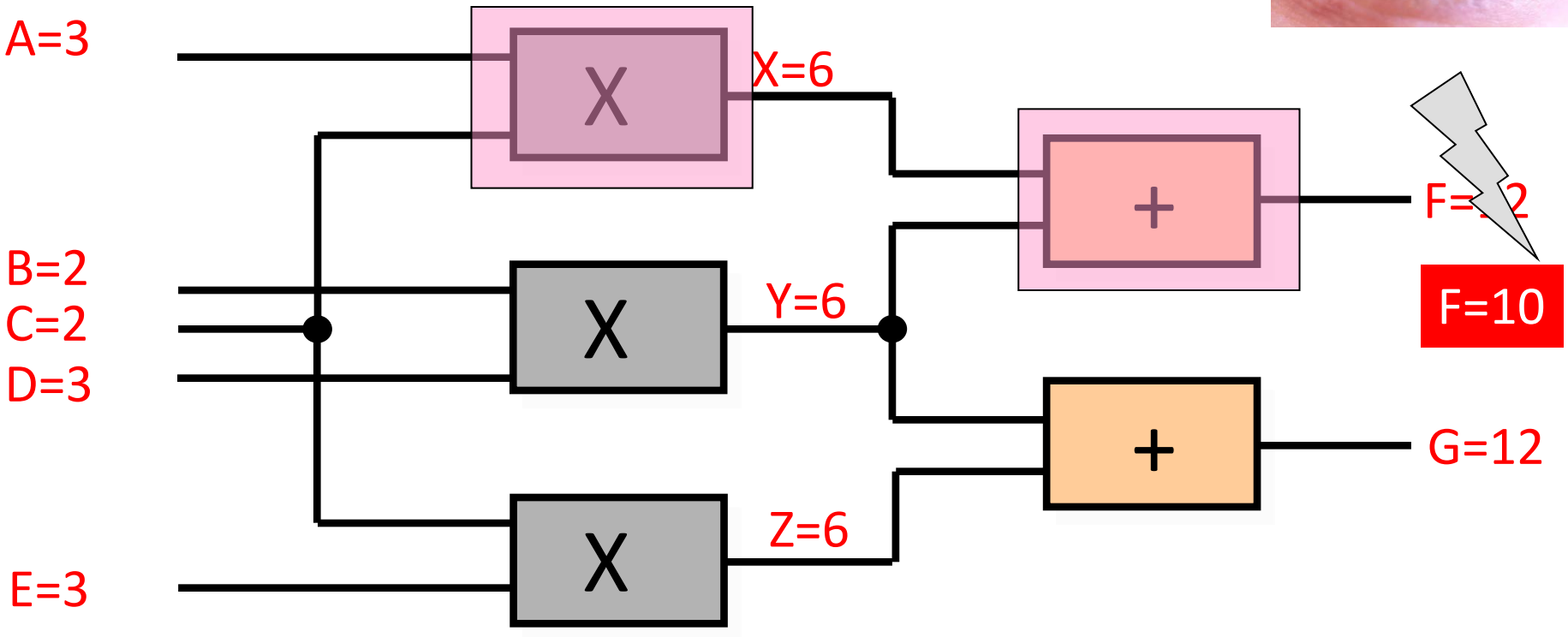
A=3; B=2; C=2; D=3; E=3;
F=10; G=12;

Diagnostic
Reasoner

Diagnosis
Repair Actions

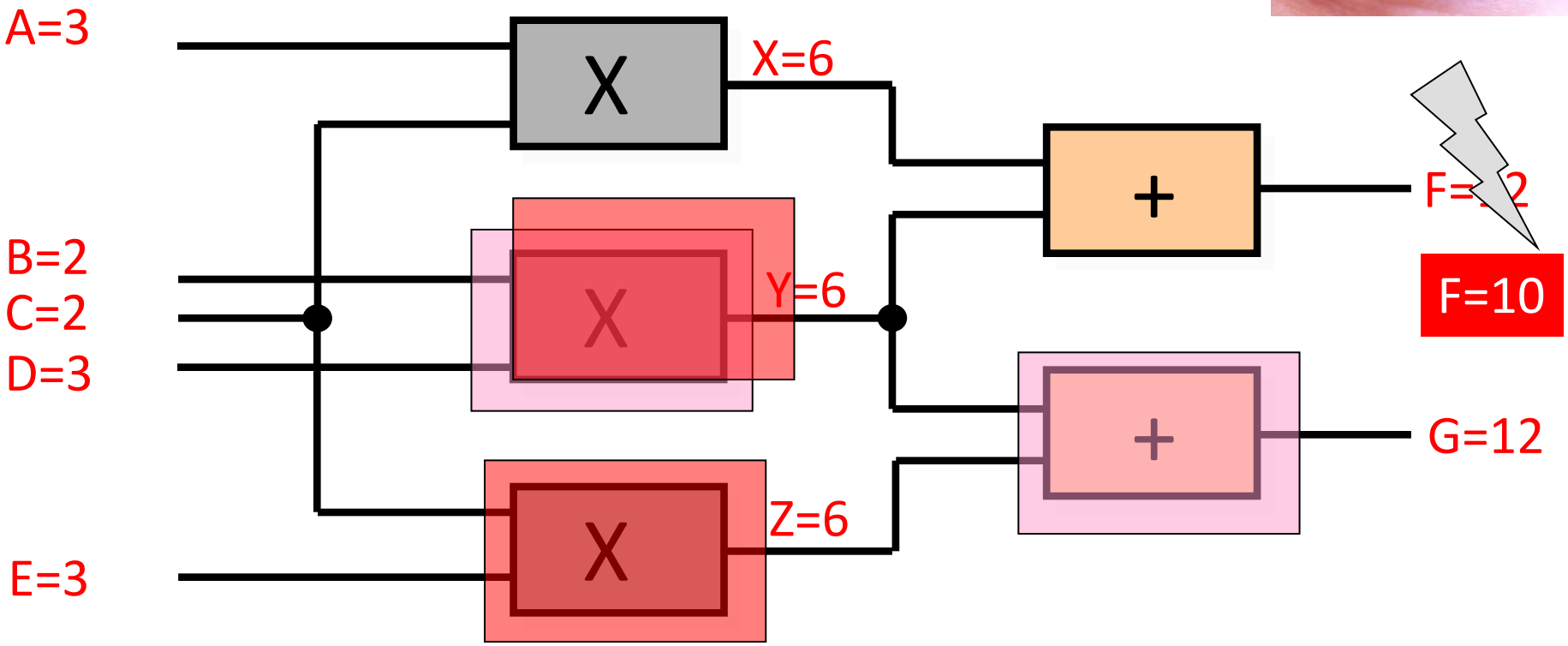
{A1}{M1}{A2M2}{M2M3}

Single Faults



Single Faults
{A1} {M1}

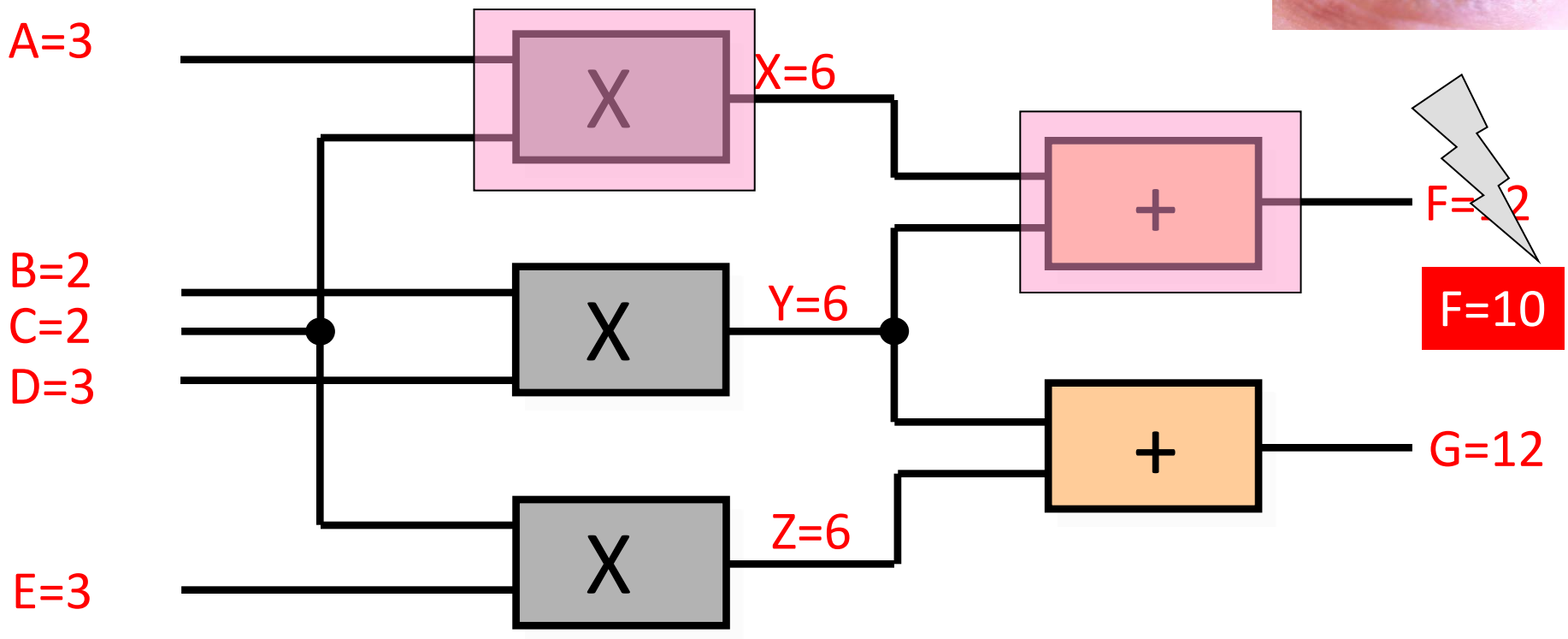
Multiple Faults



Multiple Faults
{A2 M2} {M2 M3}

Failure Modes

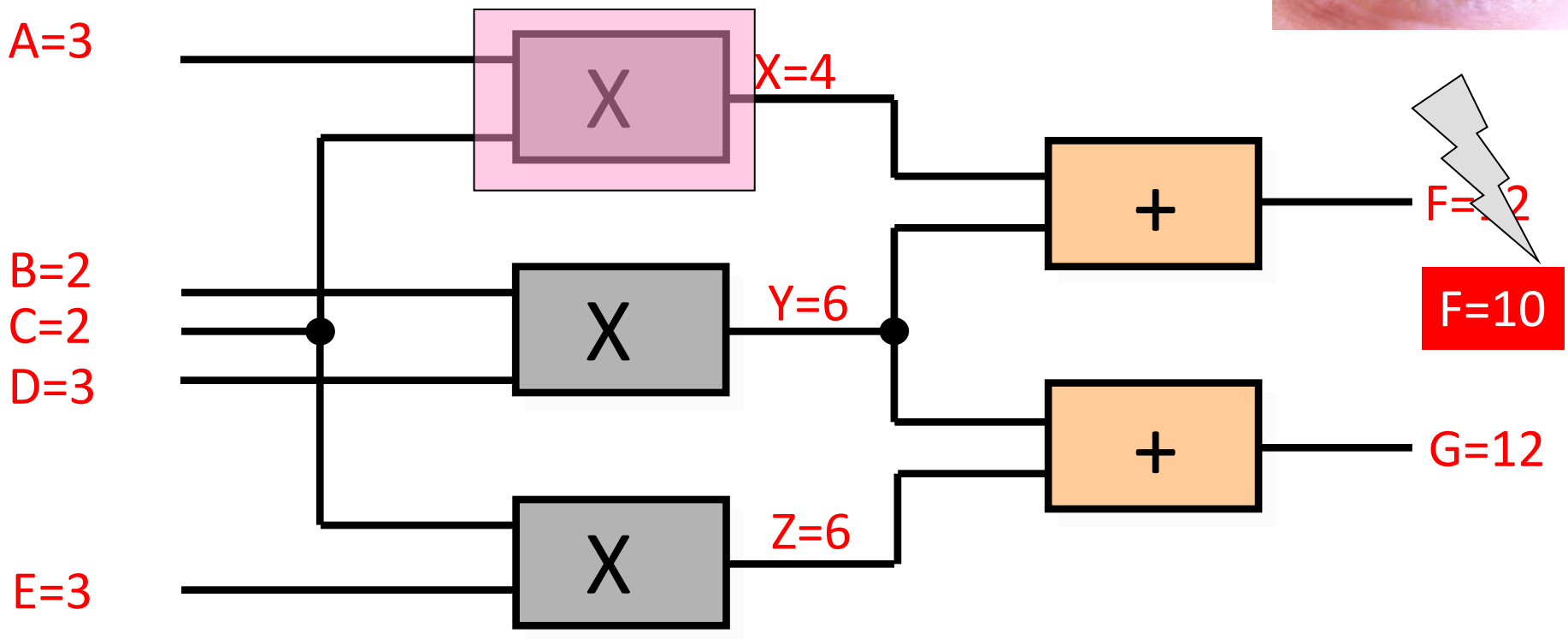
ok: out = inp1 * inp2
stuck_to_4 out = 4



Single Faults
{A1} {M1}

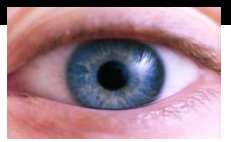
Failure Modes

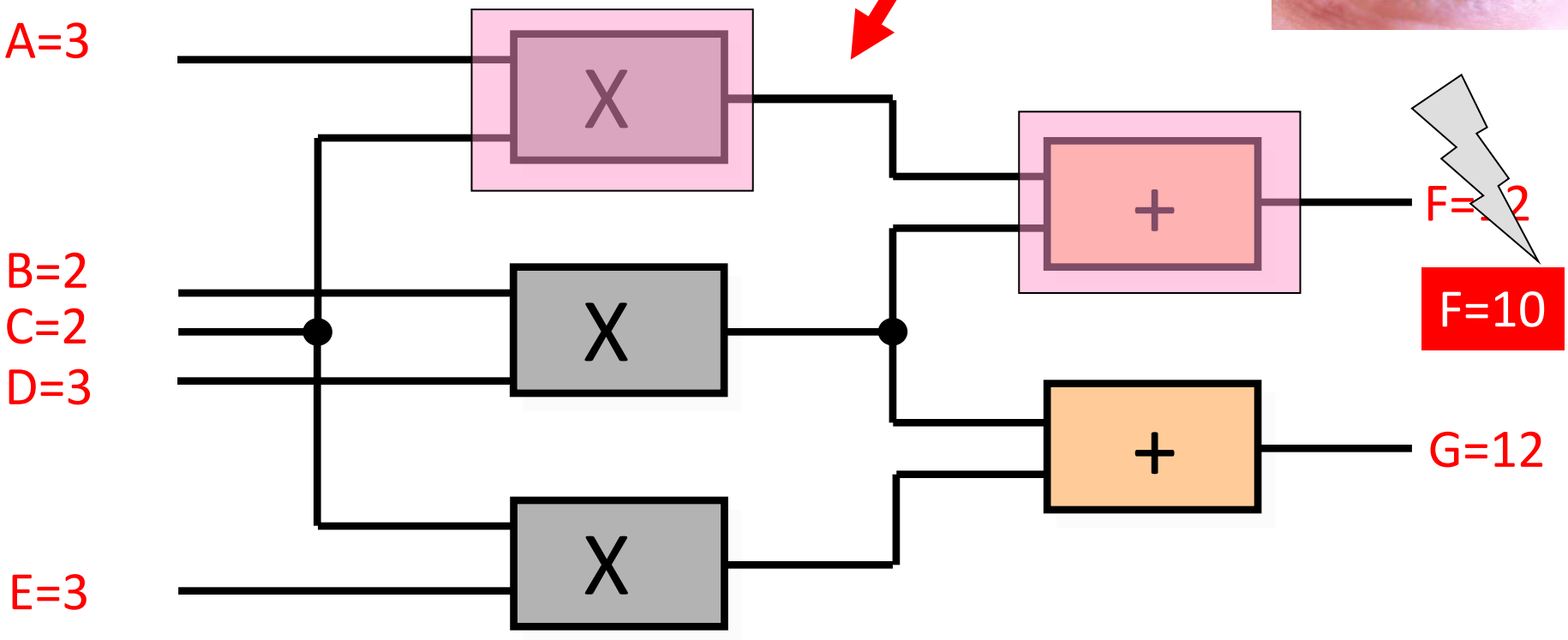
ok: out = inp1 * inp2
stuck_to_4 out = 4



Single Faults
{A1} {M1}

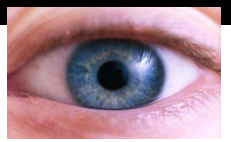
Identify Other Measurements

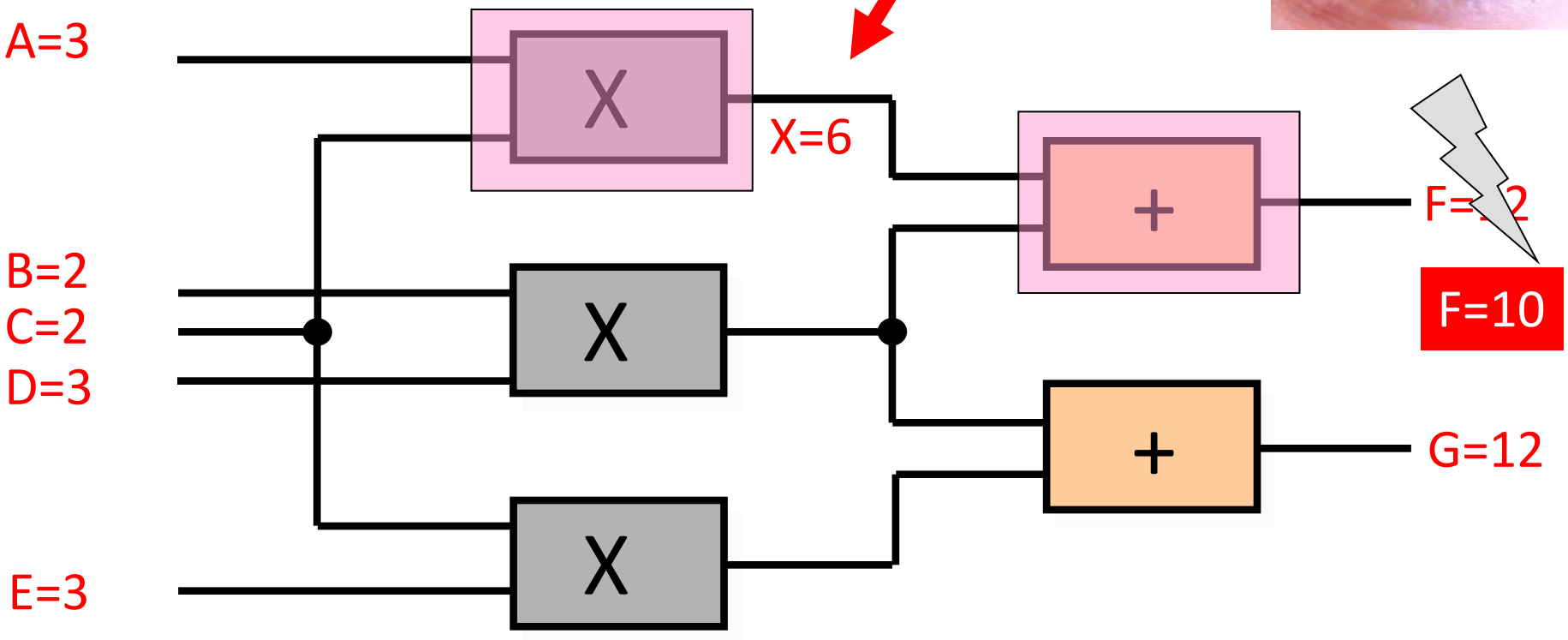




Single Faults
{A1} {M1}

Identify Other Measurements





Single Faults
{A1} {M1}

The NASA ADAPT System

ADAPT (Advanced Diagnostics and Prognostics testbed) consists of a controlled and monitored environment where faults are injected into the system in a controlled manner and the performance of the test article is carefully monitored. The hardware of the testbed is an electrical power system (EPS) of a space exploration vehicle.

The DX Competition

Track	Tier	Systems	Description
Industrial	1	ADAPT-Lite	Basic faults injected into a simplified EPS (Electrical Power System) testbed
	2	ADAPT	More complex faults injected into the full EPS distribution system
Synthetic	1	ISCAS85	Multiple faults injected into the circuits from the ISCAS85 benchmarks

Team Name	Track(s)	Algorithm Type
FACT	I1	Model-based
Fault Buster	I1, I2	Statistical
HyDE-A	I1, I2	Model-based
HyDE-S	I1	Model-based
Lydia	S	Model-based
NGDE	S	Model-based
ProADAPT	I1, I2	Probabilistic
RacerX	I1	Change detection
RODON	I1, I2, S	Model-based
RulesRule	I1	Rule-based
StanfordDA	I2	Optimization
Wizards of Oz	I1, I2	Model-based

Aspect	Tier 1	Tier 2
#Comps/Modes	37 / 93	173 / 430
Initial State	Relays closed; circuit breakers closed	Relays open; circuit breakers closed
Nominal mode changes?	No	Yes

	original					reduced
sys	|IN|	|OUT|	|COMPS|	V	C	|COMPS|
74182	9	5	19	47	75	6
74L85	11	3	33	77	118	15
74283	9	5	36	81	122	14
74181	14	8	65	144	228	15
c432	36	7	160	356	1028	59
c499	41	32	202	445	1428	58
c880	60	26	383	826	2224	77
c1355	41	32	546	1133	3220	58
c1908	33	25	880	1793	4756	160
c2670	233	140	1193	2695	6538	167
c3540	50	22	1669	3388	9216	353
c5315	178	123	2307	4792	13386	385
c2688	32	32	2416	4684	14432	1456
c7552	207	108	3512	7232	19312	545

Run-Time Architecture

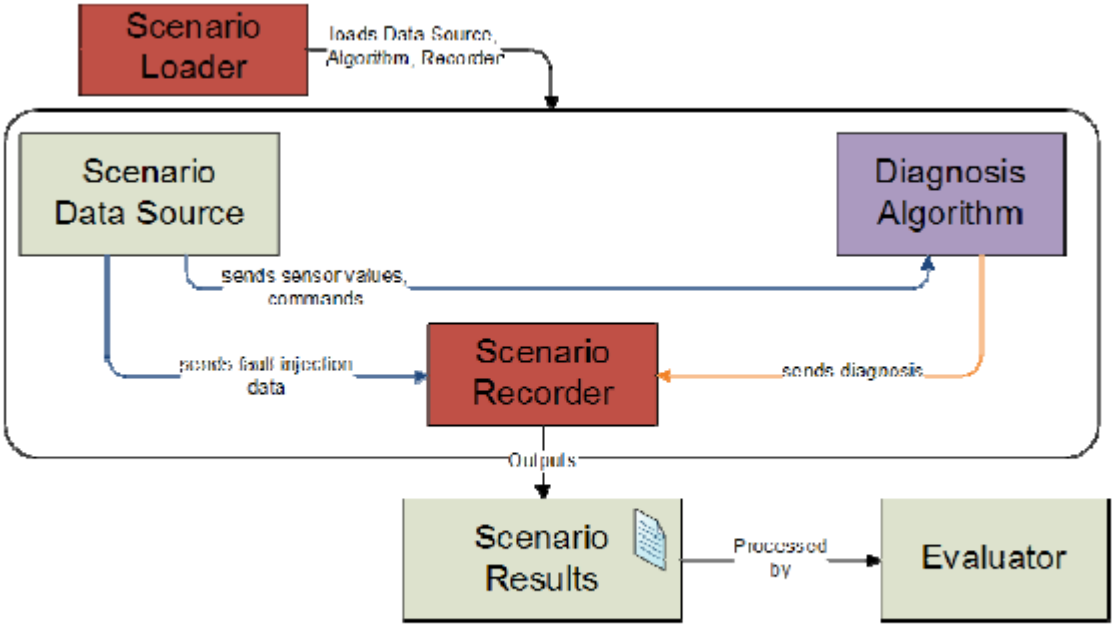


Fig. 1. Run-time architecture

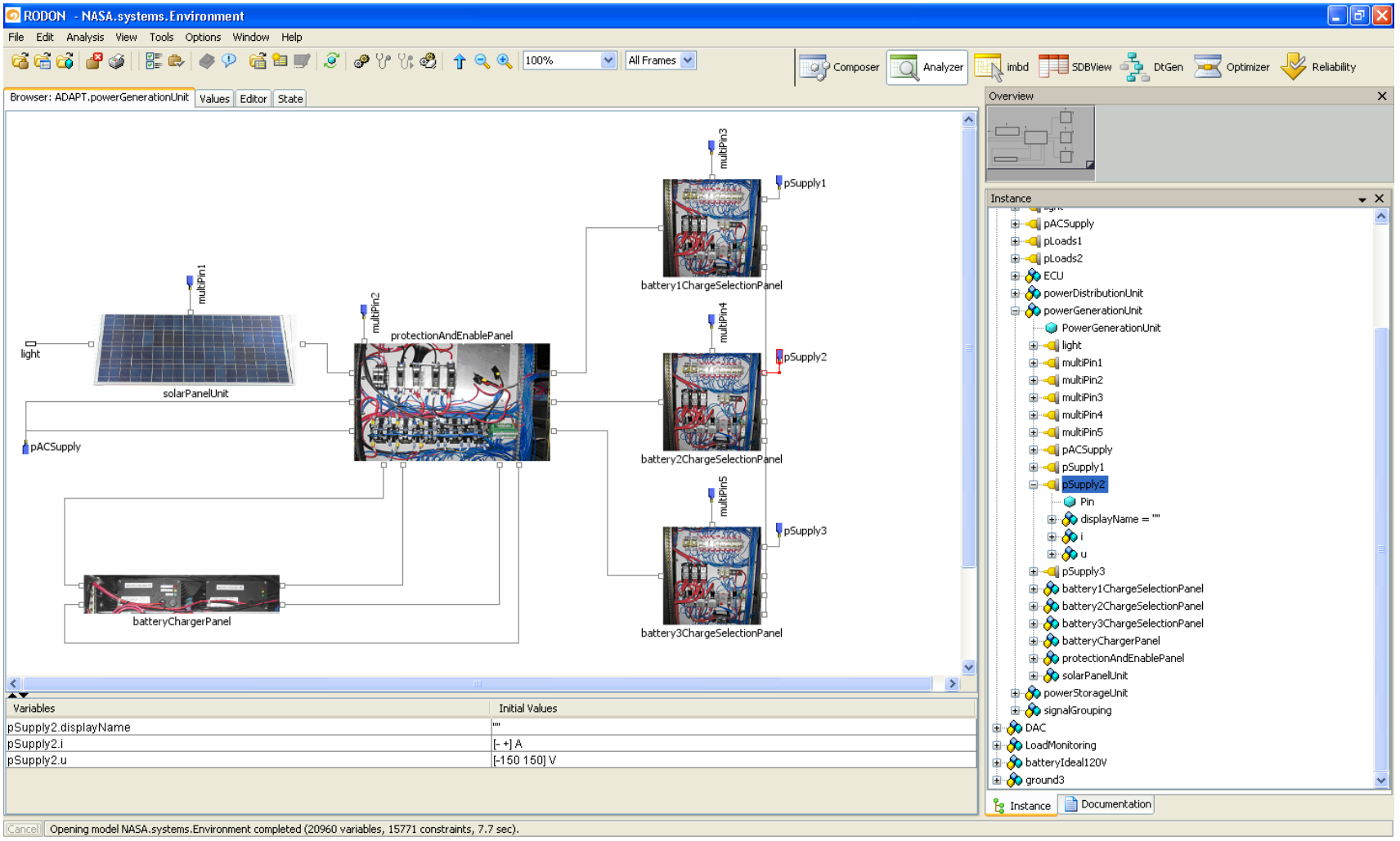
Team Name	Track(s)	Algorithm Type
FACT	I1	Model-based
Fault Buster	I1, I2	Statistical
HyDE-A	I1, I2	Model-based
HyDE-S	I1	Model-based
Lydia	S	Model-based
NGDE	S	Model-based
ProADAPT	I1, I2	Probabilistic
RacerX	I1	Change detection
RODON	I1, I2, S	Model-based
RulesRule	I1	Rule-based
StanfordDA	I2	Optimization
Wizards of Oz	I1, I2	Model-based

Kurtoglu T., S. Narasimhan, D. Garcia S. Poll, L. Kuhn, J. de Kleer, A. van Gemund, and A. Feldman. (2009b). "Towards a Framework for Evaluating and Comparing Diagnosis Algorithms." In Proceedings of the 20th International Workshop on Principles of Diagnosis (DX-09). (Stockholm, Sweden, June, 2009b).

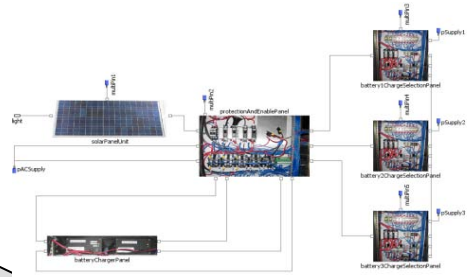
Metrics

Symbol	Name	Description	Class/Category/ Tracks Used
"Per System Description" Metrics			
M_{FPR}	False Positives Rate	Spurious faults rate	Technical / Detection/I
M_{FNR}	False Negatives Rate	Missed faults rate	Technical / Detection/I
M_{FDA}	Detection Accuracy	Correctness of the detection	Technical / Detection/I
"Per Scenario" Metrics			
M_{fd}	Fault Detection Time	Time for detecting a fault	Temporal / Detection/I,S
M_{fi}	Fault Isolation Time	Time for last persistent diagnosis	Temporal / Isolation/I,S
M_{ia}	Classification Errors	Number of mode classification errors	Technical / Isolation/I
M_{utl}	Diagnostic Utility	Cost related to component replacements due to incorrect diagnosis	Technical / Isolation/S
M_{cpu}	CPU Load	CPU time spent	Computational / Detection & Isolation/I,S
M_{mem}	Memory Load	Memory allocated	Computational / Detection & Isolation/I,S

Model of the NASA ADAPT Satellite System



General RODON Achitecture



Knowledge Representation
Declarative Language
Rodelica

Knowledge Base
Constraint Network

RODON
Inference Engine

Beliefs

Assumption Truth
Maintenance System

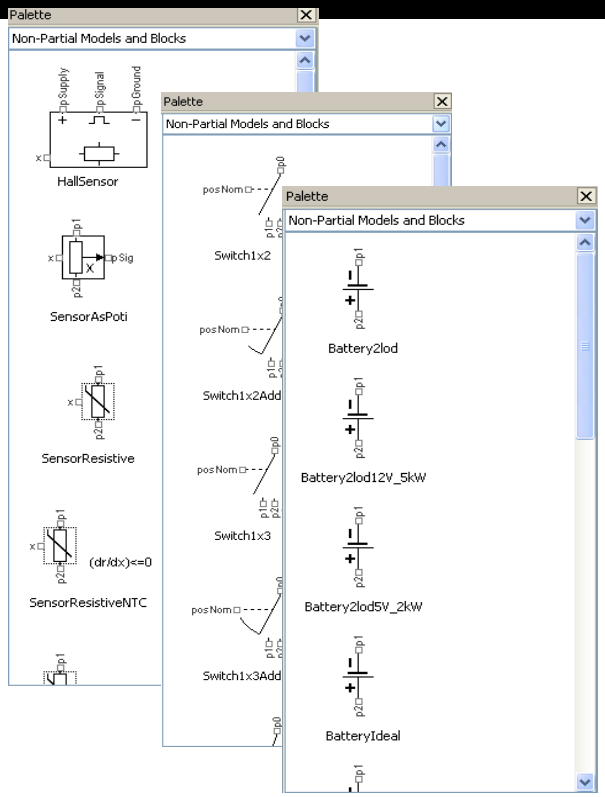
Working Memory

Conclusions
Contradictions

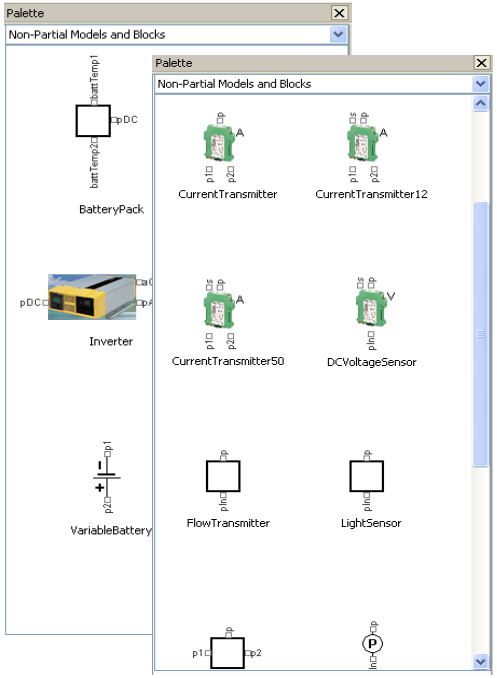
GDE [de Kleer and Williams 1987]
G+DE [Heller and Struss. 2001]

[de Kleer 1986]

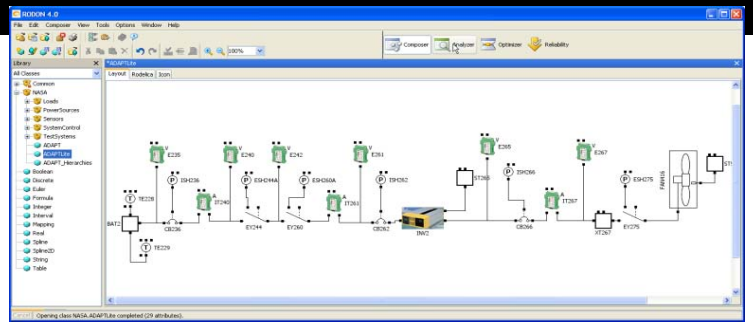
The Model Building Process

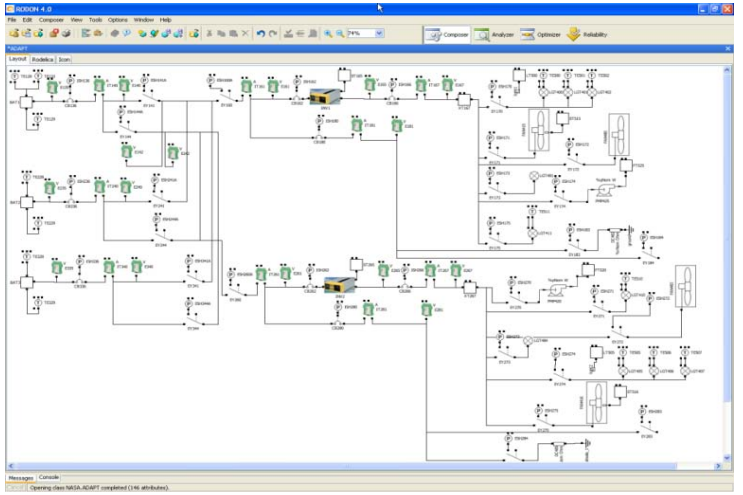


Generic
Component
Libraries



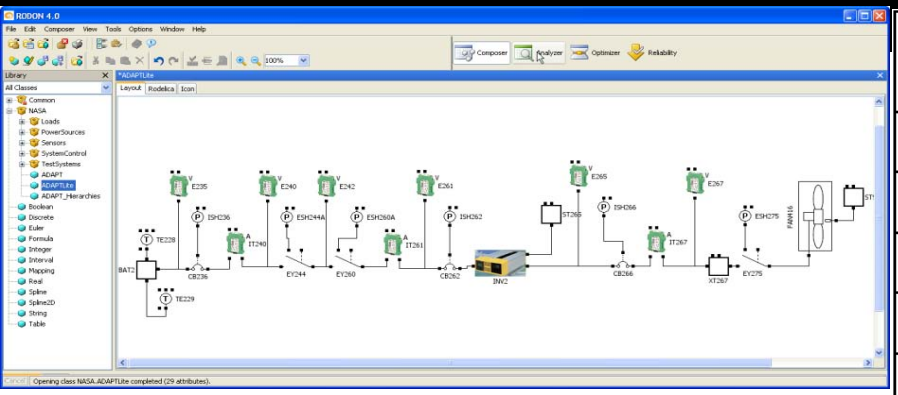
ADAPT Specific
Component Libraries
(derived from generic components)





ADAPT Tier1 and Tier2
assembled from model
library components

Strategy Adopted for ADAPT Tier1

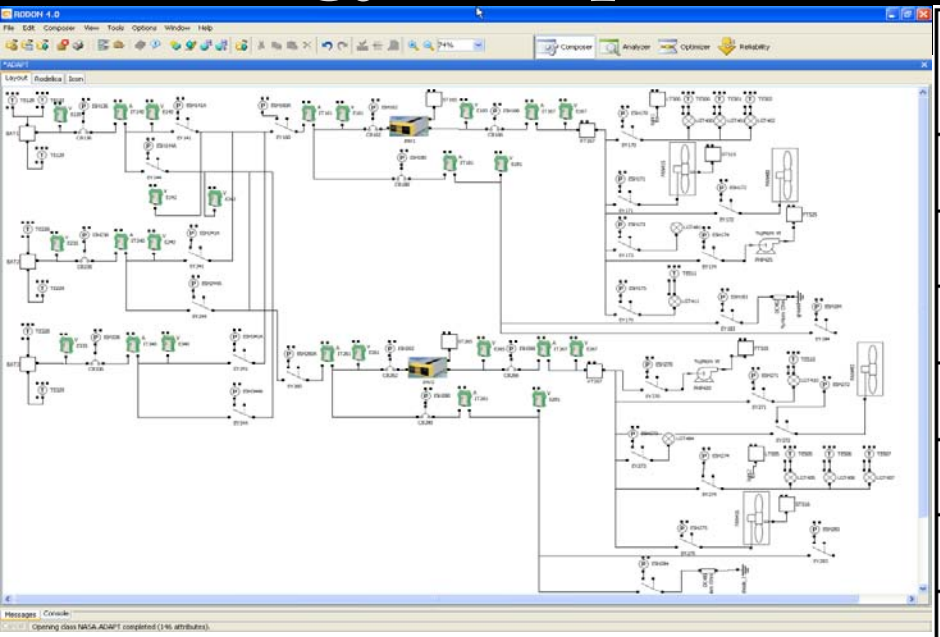


	Weight	RODON	Wizards Of Oz	Fault Buster	ProADAPT	HyDE-A	HyDE-S	RulesRule	FACT	RacerX
FP Rate	**1.3**	0.0645	0.0000	0.1333	0.0333	0.0000	0.2000	0.8246	0.2813	0.0645
Ranking		4	**1**	6	3	**1**	7	9	8	4
Points		6	9	4	7	9	3	1	2	6
FN Rate	**1.3**	0.0968	0.5000	0.3438	0.0313	0.4688	0.0741	0.0000	0.0667	0.1613
Ranking		5	9	7	**2**	8	4	**1**	3	6
Points		5	1	3	8	2	6	10	7	4
Det Acc	**0.3**	0.9194	0.7419	0.7581	0.9677	0.7581	0.8548	0.2419	0.8226	0.8871
Ranking		**2**	8	6	**1**	6	4	9	5	3
Points		8	2	3.5	10	3.5	6	1	5	7
Class Errors	**2.2**	10.000	24.000	32.000	2.000	26.649	26.000	76.000	25.000	32.000
Ranking		**2**	3	7	**1**	6	5	9	4	7
Points		8	7	2.5	10	4	5	1	6	2.5
T_det (ms)	**2.2**	218	11530	1893	1392	13223	130	1000	373	126
Ranking		3	8	7	6	9	**2**	5	4	**1**
Points		7	2	3	4	1	8	5	6	10
T_iso (ms)	**1.5**	7205	11626	9259	4084	13840	653	282	9796	999999
Ranking		4	7	5	3	8	**2**	**1**	6	9
Points		6	3	5	7	2	8	10	4	1
CPU (ms)	**0.6**	11766	1039	2039	1601	24795	513	117	1767	139
Ranking		8	4	7	5	9	3	**1**	6	**2**
Points		2	6	3	5	1	7	10	4	8
Mem (kb)	**0.6**	26679	1781	2539	1680	5447	5795	3788	4340	3572
Ranking		9	**2**	3	**1**	7	8	5	6	4
Points		1	8	7	10	3	2	5	4	6
FINAL SCORES:		59.850	46.300	35.750	72.800	31.750	59.500	51.800	50.400	51.850
FINAL RANK:		**2**	7	8	**1**	9	3	5	6	4

- Memory and CPU are very high for RODON (we knew that we are will loose those points)
- The strategy was to score high on the **Detection Acuracy, Class Errors and T_Det**

Kurtoglu T., S. Narasimhan, S. Poll, D. Garcia, L. Kuhn, J. de Kleer, A. van Gemund, and A. Feldman. (2009a). "First International Diagnosis Competition – DXC'09." In Proceedings of the 20th International Workshop on Principles of Diagnosis (DX-09). (Stockholm, Sweden, June, 2009a).

Strategy Adopted for ADAPT Tier2



	Weight	RODON	Wizards Of Oz	Fault Buster	ProADAPT	HyDE	Stanford
FP Rate	**1.3**	0.5417	0.5106	0.8143	0.0732	0.0000	0.3256
Ranking		5	4	6	**2**	**1**	3
Points		5	6	4	8	10	7
FN Rate	**1.3**	0.0972	0.0959	0.2400	0.1392	0.3000	0.0519
Ranking		3	**2**	5	4	6	**1**
Points		7	8	5	6	4	10
Det Acc	**0.3**	0.7250	0.7417	0.4250	0.8833	0.8000	0.8500
Ranking		5	4	6	**1**	3	**2**
Points		5	6	4	10	7	8
Class Errors	**2.2**	84.067	159.248	130.000	76.000	121.569	110.547
Ranking		**2**	6	5	**1**	4	3
Points		8	4	5	10	6	7
T_det (ms)	**2.2**	3490	30742	14099	5981	17610	3946
Ranking		**1**	6	4	3	5	**2**
Points		10	4	6	7	5	8
T_iso (ms)	**1.5**	36331	47625	37808	12486	21982	14103
Ranking		4	6	5	**1**	3	**2**
Points		6	4	5	10	7	8
CPU (ms)	**0.6**	80261	23387	5798	3416	29612	963
Ranking		6	4	3	**2**	5	**1**
Points		4	6	7	8	5	10
Mem (kb)	**0.6**	29878	7498	10261	6539	20515	5912
Ranking		6	3	4	**2**	5	**1**
Points		4	7	6	8	5	10
FINAL SCORES:		70.500	51.400	52.400	83.200	61.000	81.500
FINAL RANK:		3	6	5	**1**	4	**2**

- The strategy was again to score high on the **Det_acc**, **Class_Err** and **T_dec**.
- The diagnosis engine was ignoring the transients during the switching.
- We have not noticed that the training data contained one triple fault scenario. The DA was configured to stop at double faults.
- Recomputing the scenarios by taking into account triple faults would have not changed the final clasification

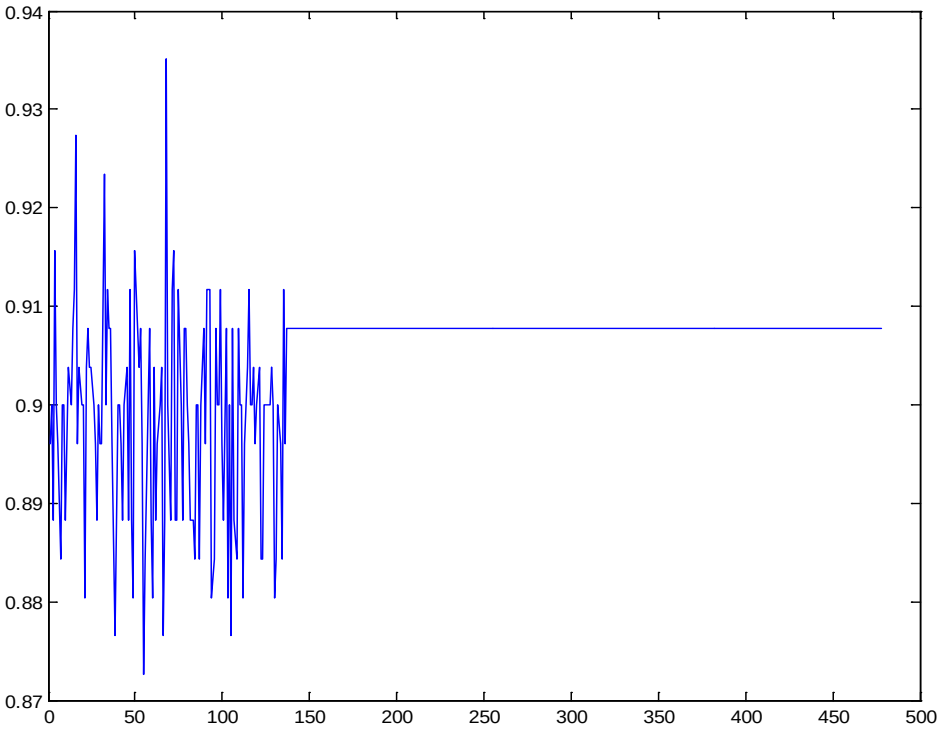
Strategy Adopted for the Synthetic Track

		Lydia			NGDE			RODON		
circuit	#comp	cpu	mem	utl	cpu	mem	utl	cpu	mem	utl
74182	19	51	154	0.4137	6335	11540	0.4793	3043	19773	0.4448
74L85	33	68	223	0.2433	6365	11784	0.3098	3888	20979	0.1952
74283	36	60	229	0.1580	6385	12231	0.1553	5351	20637	0.1147
74181	65	64	401	0.1504	6619	14625	0.1931	12527	25432	0.1417
c432	160	115	878	0.0871	7520	17868	0.2096	22621	36811	0.0906
c499	202	130	1094	0.0622	20347	32649	0.0699	23504	39872	0.0089
c880	383	203	1945	0.0483	13718	28622	0.0401	20347	43687	0.0182
c1355	546	296	2759	0.0295	22550	37930	0.0246	23253	33530	0.0012
c1908	880	538	4134	0.0179	26171	39843	0.0150	27718	38557	0.0180
c2670	1193	937	5867	0.0647	20537	61722	0.1076	35680	43063	0.0442
c3540	1669	1674	7900	0.0319	27022	82045	0.0407	0	0	0.0000
c5315	2307	3091	11316	0.0165	30926	93116	0.0275	0	0	0.0000
c6288	2416	3530	12037	0.0008	17483	102420	0.0563	0	0	0.0000
c7552	3512	11817	16679	0.0317	37989	125910	0.0283	0	0	0.0000
	Averaged	1613	4687	0.0969	17855	48022	0.1255	12709	23024	0.0770
	Per Metric Rank	1	1	2	3	3	1	2	2	3
	Points	10	10	8	7	7	10	8	8	7
	Metric Weight	1.5	1.5	7	1.5	1.5	7	1.5	1.5	7
	Final Scores		86			91			73	
	Final Rank		2			1			3	

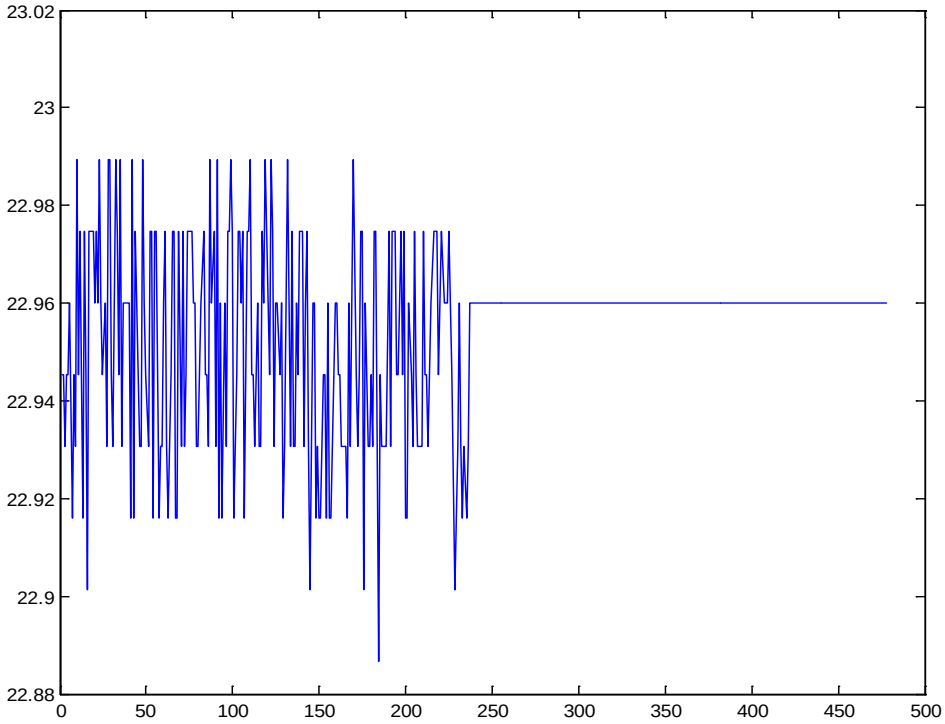
Circuit	utl	nutl
74182	0,448	0,4448
74L85	0,1952	0,1952
74283	0,1147	0,1136
74181	0,1417	0,1415
c432	0,0906	0,0904
c499	0,0089	0,0132
c880	0,0182	0,0182
c1355	0,0012	0,0012
c1908	0,018	0,0026
c2670	0,0442	0,0442
c3540	0	0,0566
c5315	0	0,0086
c6288	0	0,0008
c7552	0	0,0239
	0,077193	0,082486

- Compute as many candidates as possible in the given time until timeout
- c3540, c5315, c6288, c7552 were not loaded during the competion. RODON needs 35 sec to load c7552 on a 2GHz computer
- Recomputing the scenarios with a bigger start up time would have not changed the final clasification
- The training data training had scenarios with up to 5 simulateneous faults. The competition data had scenarios with up to 26 simultaneous faults.

ADAPT – Tier Difficulties

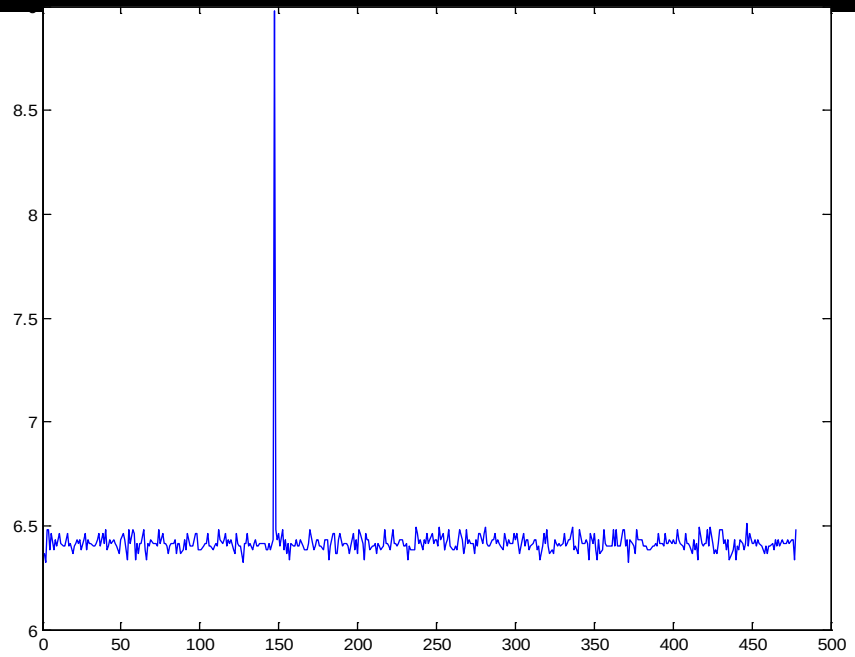


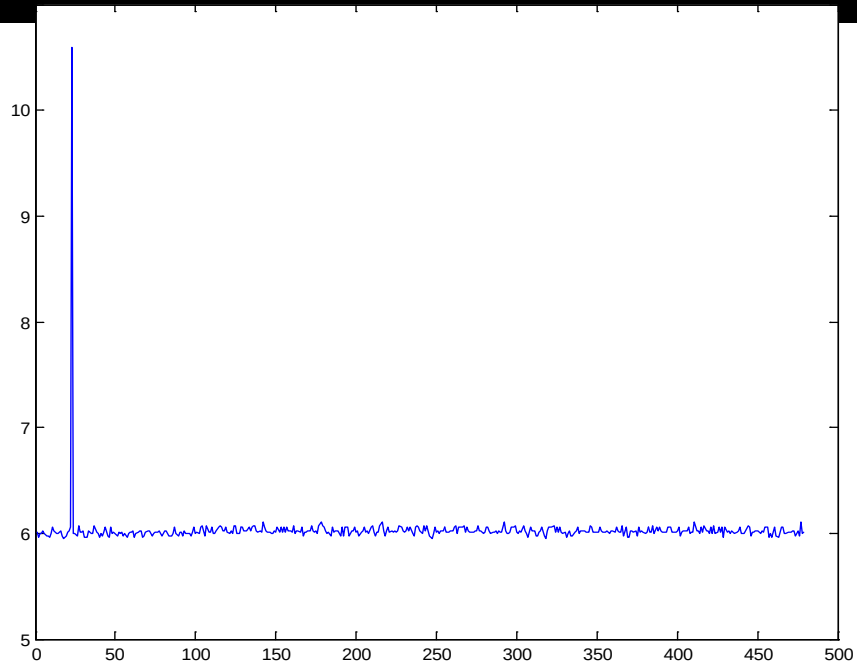
- Exp_699_028_pb_t1f
  - IT267 Stuck not easily detected



- Exp_699_063_pb_t1f
  - E261Stuck not easily detected

ADAPT – Tier Difficulties

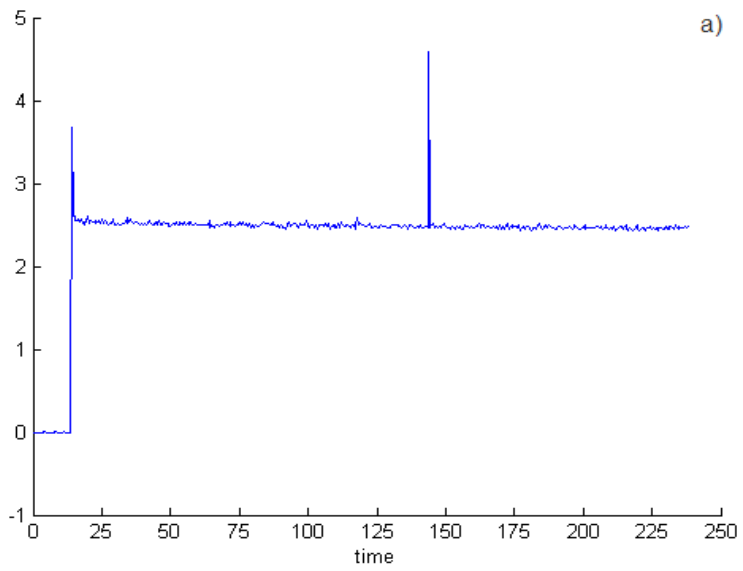


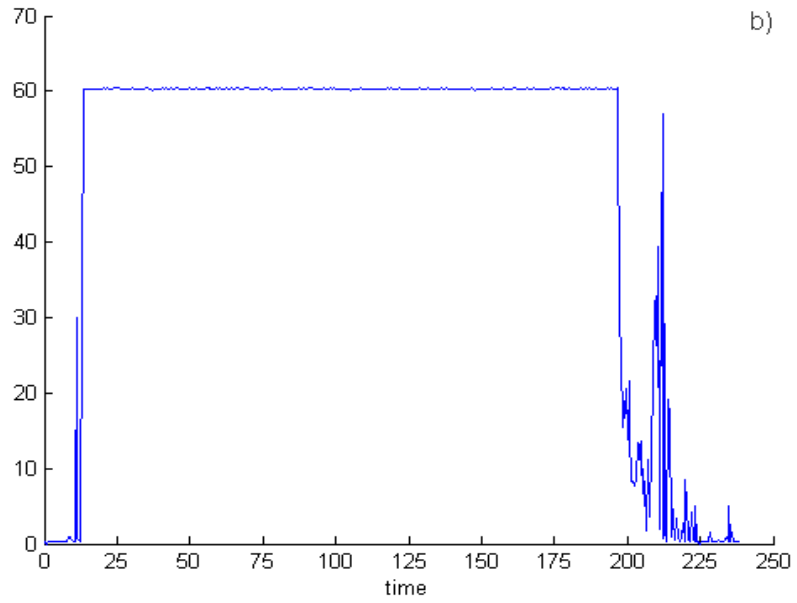


- Exp_699_071_pb_t1
  - Peak at the IT261

- Exp_725_pb_t1
  - Peak at the IT240

ADAPT – Tier Difficulties





- Exp_616_pb_t2
  - A noise in the current sensor IT 167 determined the DA to report a double fault.

- Exp_620_pb_t2
  - A noise in ST165 determined the DA to report a double fault

Conclusions

- Lack of system knowledge and interaction with the system engineers was a serious disadvantage for our team.
- We welcome the idea of the DX Competition and we are looking forward to more challenging problems.
- We would like to thank the DX Competition Challenge organizers to setting up the competition framework, providing a framework and making this possible and NASA Ames for the valuable feedback during this project.