Change Propagation Analysis in Complex Technical Systems

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Complex Industrial Systems: Modeling, Verification and Optimization

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Olivier L. de Weck, Gergana Bounova
deweck@mit.edu, gergana@mit.edu
Department of Aeronautics & Astronautics
Engineering Systems Division

Outline

- Background and Motivation
  - Swiss F/A-18 Aircraft Experience (1991-1997)
  - Literature Review – Previous Work
  - Research Questions
- Change Propagation Analysis
  - Analysis of a 9-year Sensor System Design Project
  - Motifs and Change Patterns
- Discussion and Future Work
  - Tracing the Evolution of Complex Systems
  - Apriori Change Prediction

Background and Motivation

Swiss F/A-18 Experience

U.S. Navy Version C/D (1987)

fighter and attack
3000 flight hours
90 min average sortie
max 7.5g positive

Swiss Version (1993)

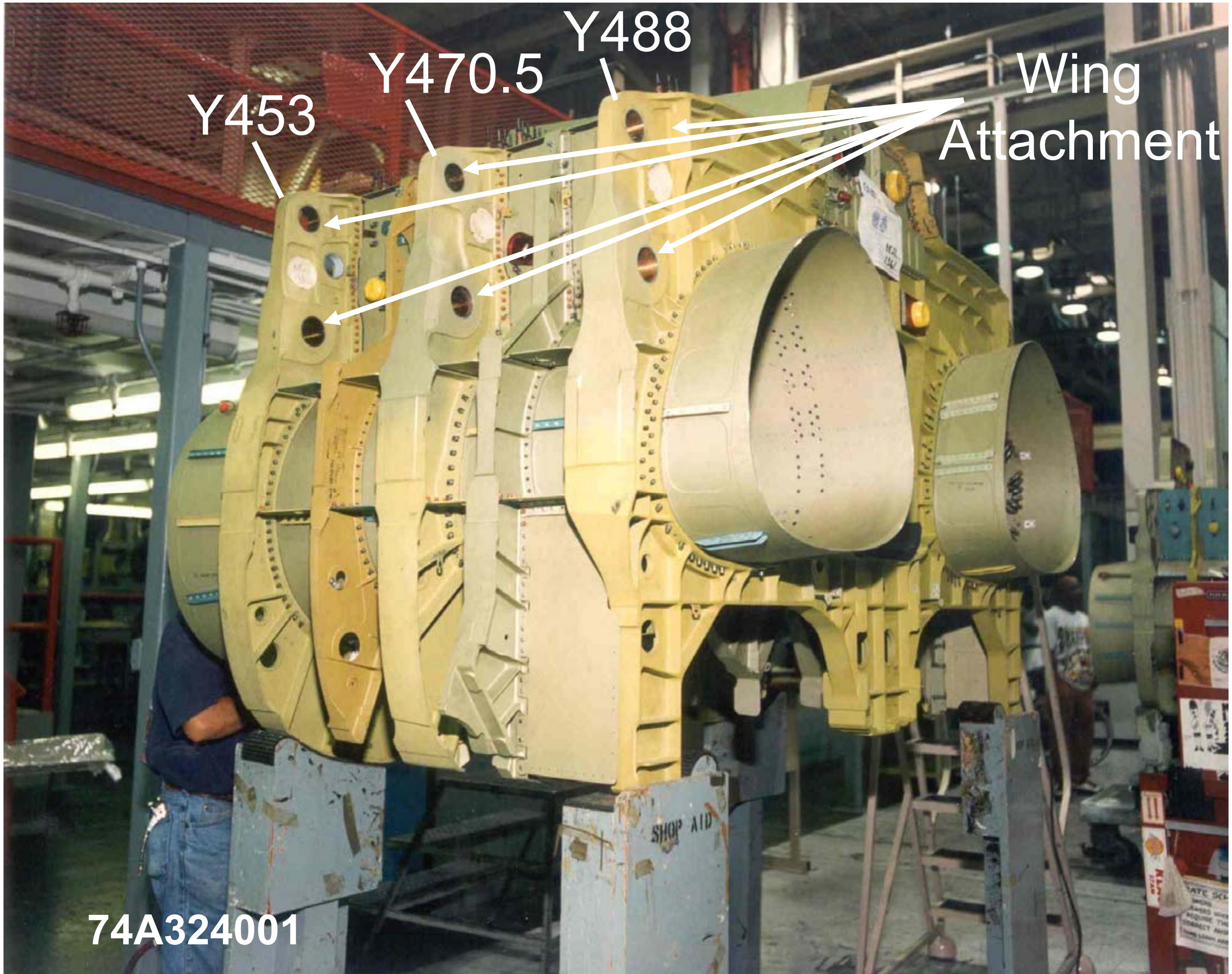
interceptor
5000 flight hours
40 min average sortie
max 9.0g positive

"Redesign"

(Engineering Change)

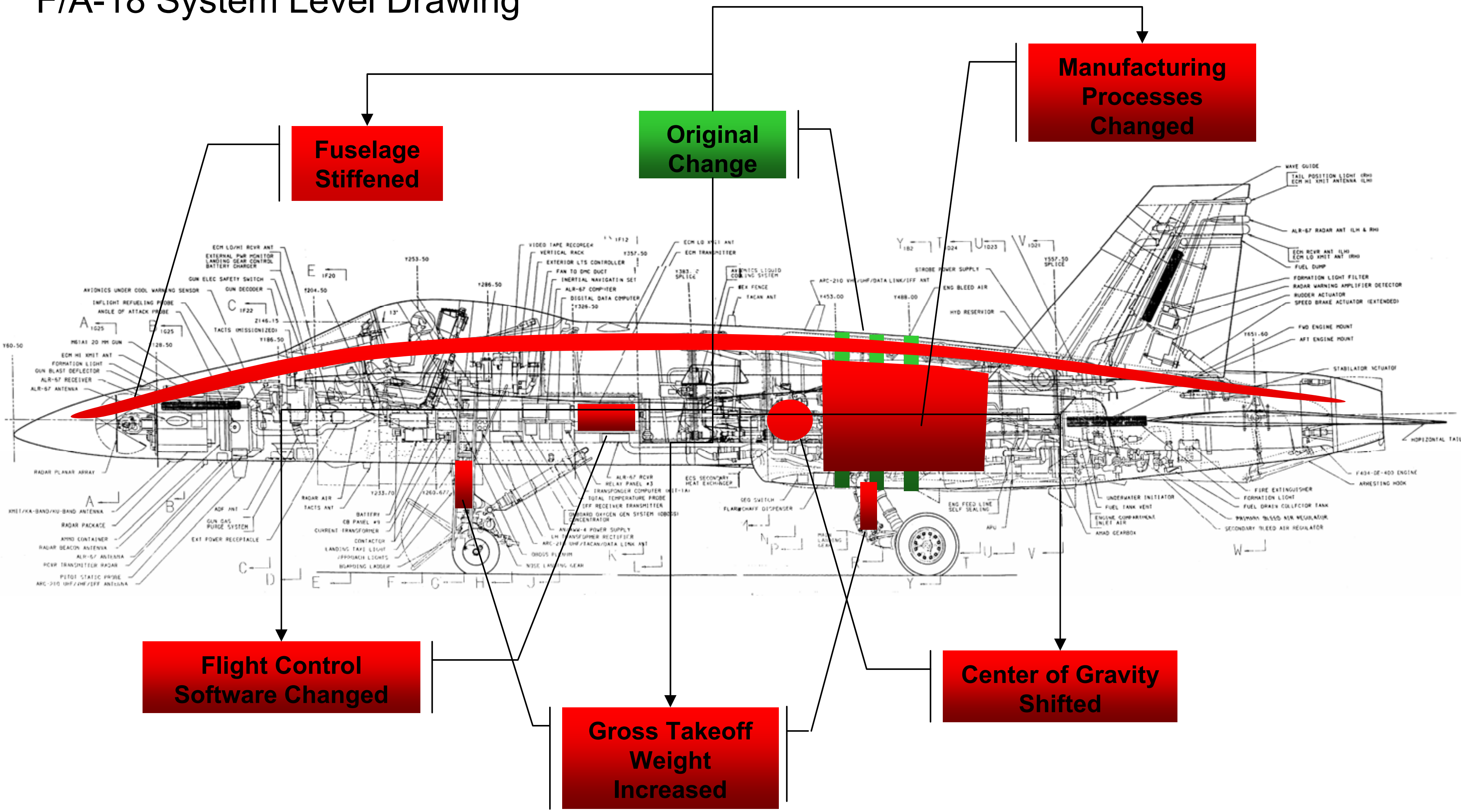
- **Approach**
  - Apply new operational usage spectrum to existing configuration
  - Find those locations in the system which do not comply
  - Apply selective, prioritized <u>local redesign</u> one-element-at-a-time
  - Example: Center barrel, wing-carry-though bulkheads Al → Ti

F/A-18 Center Barrel Section



F/A-18 Complex System Change

F/A-18 System Level Drawing



F/A-18 Lessons Learned

- Changes increased cost per aircraft by O(~$10M)
  - encountered "surprises" along the way
- Changing a system (or product) after its initial design is
  - often required to accommodate new requirements
  - expensive, and time-consuming if change not anticipated
- Change propagation
  - some changes are local and remain local
  - other changes start local, but propagate through the system
  - "Switching costs" include: engineering redesign cost (hardware and software), manufacturing changes, change in operational costs, recertification, others …

Literature Review – Previous Work

- Traditional Systems Engineering Methods (QFD, DSM,…)
  - Hauser, LR.; Clausing, D. The House of Quality. **Harvard Business Review**,. Vol. 66, No. 3, May-June 1988,. pp, 63-73
  - say very little about system change over time
- Engineering Changes
  - C. Eckert, P. Clarkson, and W. Zanker, Change and customisation in complex engineering domains, **Research in Engineering Design**, 15(1) (2004), 1–21
  - External vs. Internal Changes, Classification in Multipliers, Absorbers, etc…
- Design for Changeability
  - E. Fricke and A.P. Schulz, Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle, **Systems Engineering**, 8(4) (2005)
  - Fundamental & Supporting Principles for Changeability

How to deal with changes in complex products and systems?

Research Questions

- What are sources of changes in system design (during design and/or operations)?
  - exogenous uncertainties, internal sources of change
- How can the amount and type of change and change propagation paths be
  - analyzed for existing or past systems? (a posteriori analysis)
  - predicted for future systems? (a priori analysis)
- What causes lock-in (=the inability to change) and how can it be mitigated?
  - Where should flexibility be embedded?
  - How much is it worth?
  - Is there an optimal degree of flexibility in system design?

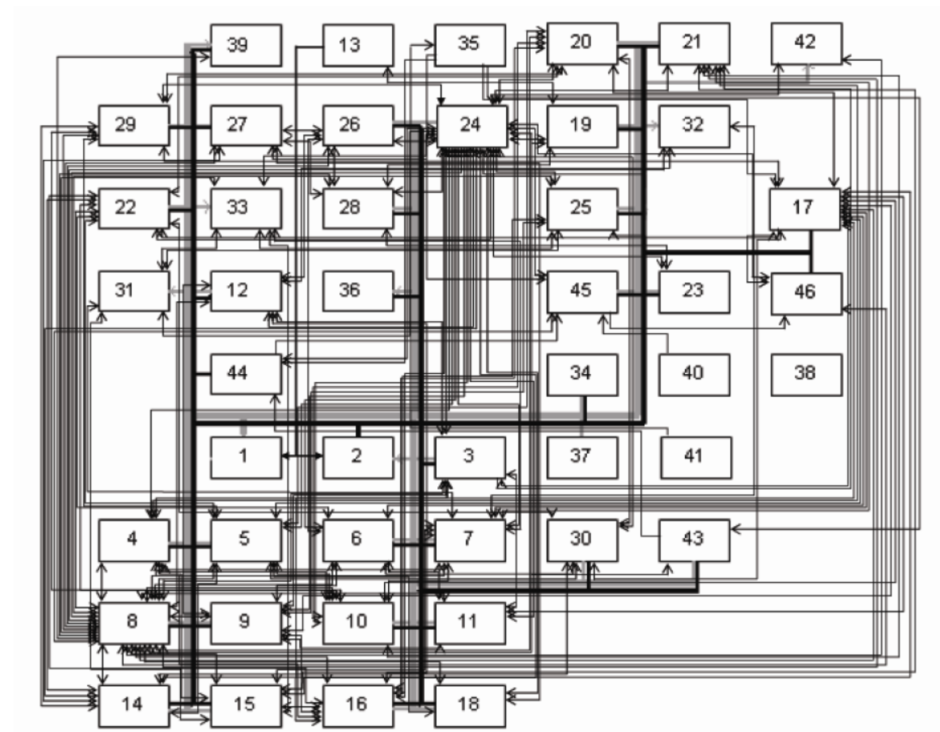
Change Propagation Analysis

Giffin M, de Weck O.L., Bounova G., Keller R., Eckert C., Clarkson J., "Change Propagation Analysis in Complex Technical Systems", DETC2007-34652, Proceedings of ASME IDETC/CIE 2007, September 4-7, Las Vegas, NV, 2007

under review Journal of Mechanical Design

System Description

- Complex Sensor System
  - Uses electromagnetic waves, complex hardware, software, human operators
  - Derivative of earlier system
  - 9 Year development
- 46 Areas
  - Hardware
  - Software
  - Program Documentation
- System Map (graph)
  - Interconnections between areas



Data Set

- Change Request Database
  - technical, managerial, procedural
  - track parent, child, siblings by areas with unique ID number
  - chronologically numbered IDs
  - 41,500 Change Requests
  - Largest Published to date !

- Data Mining Procedure
  - Export from DBMS to text file
  - Written into MySQL database with Perl scripts
  - Equivalent to a MS Word document with 120,000 pages
  - Sorting, Filtering, Anonymizing
  - Write simplified change request format (see right side)

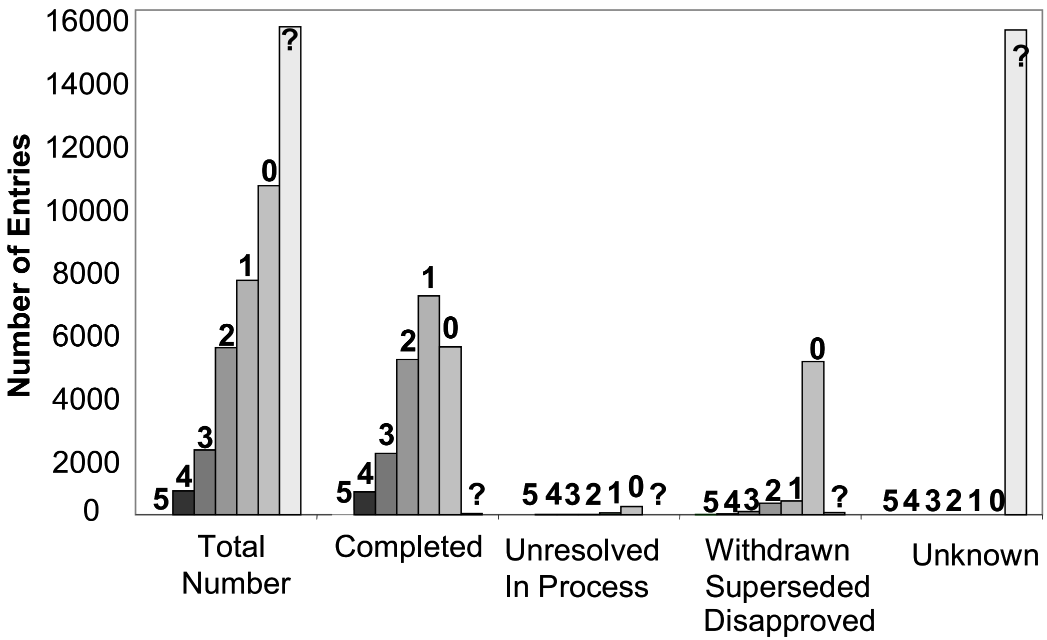
Typical Change Request

ID Number	12345
Date Created Date Last Updated	06-MAR-Y5 10-JAN-Y6
Area Affected	19
Change Magnitude	3
Parent ID	8648
Children ID(s)	15678, 16789
Sibling ID(s)	9728
Submitter	eng231
Assignees	eng008 eng231 eng018
Associated Individuals	Admin_001 Engineer_271
Stage Originated, Defect Reason	[blank], [blank]
Severity	[blank]
Completed?	1

Detailed Research Questions

- What are some significant statistical observations?
- Are most change requests isolates or do they occur in larger sets of connected changes?
- If larger networks of changes occur, do they originate from a single instigating parent change or are the actual patterns of change propagation more complex?
- Are changes distributed unevenly throughout the system and if so, do some areas act as multipliers or absorbers of changes?
- Is the amount of activity, i.e. the rate at which new change requests are generated, constant over time?
- What implications for the choice of product architecture and design change process management can be derived from the analysis, if any?

Initial Analysis



5	Total SLOC ≥ 1000	≥ 200 Total Hours
4	200 ≤ Total SLOC < 1000	80 ≤ Total Hours < 200
3	50 ≤ Total SLOC < 200	40 ≤ Total Hours < 80
2	10 ≤ Total SLOC < 50	8 ≤ Total Hours < 40
1	1 ≤ Total SLOC < 10	1 ≤ Total Hours < 8
0	Total SLOC < 1	Total Hours < 1

There is an inverse relationship between expected change magnitude and its frequency of occurrence.

Very large changes are rather infrequent while small changes on the other hand are commonplace.

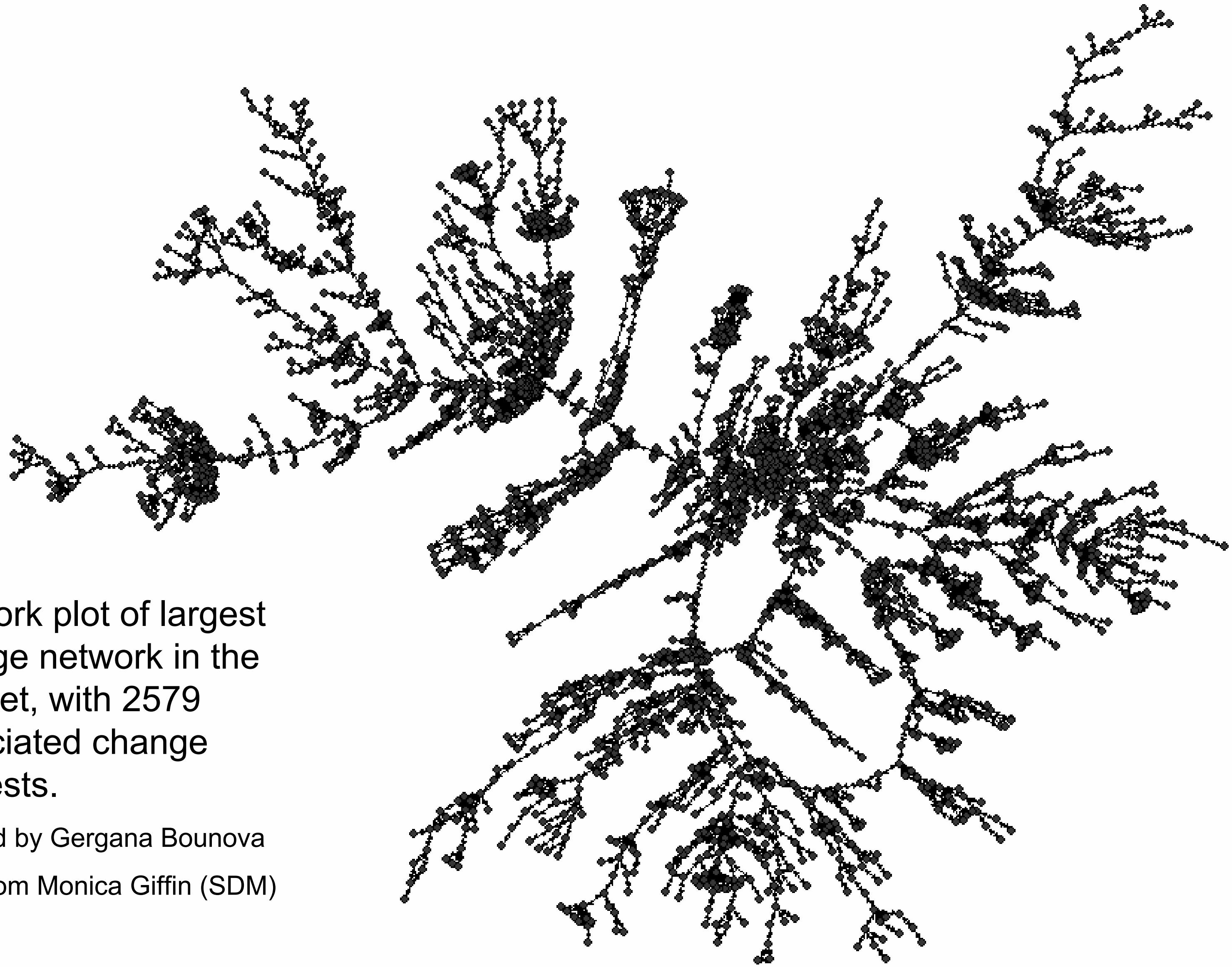
Nearly half the small (magnitude 0) changes were either withdrawn, superseded or disapproved (46.6%), whereas nearly all the large changes (magnitude 5) were approved and carried out to completion (96.7%).

Change Networks

- Apply Graph Theory to extract networks of connected changes
  - parent-child changes
  - sibling changes
- Most changes are only loosely connected
  - 2-10 related changes
- Some large networks emerged
- Question: do these networks emerge from a single initial change?

(rank)	(connected changes)
1	2579
2	424
3	170
4	87
5	64

Change Propagation Network



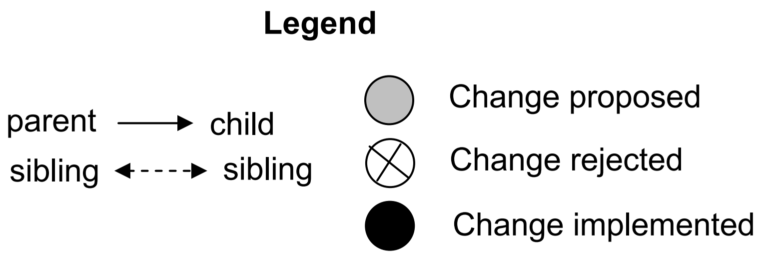
Network plot of largest change network in the dataset, with 2579 associated change requests.

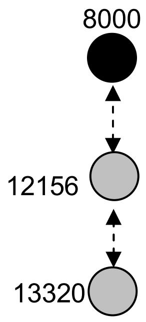
Created by Gergana Bounova

Data from Monica Giffin (SDM)

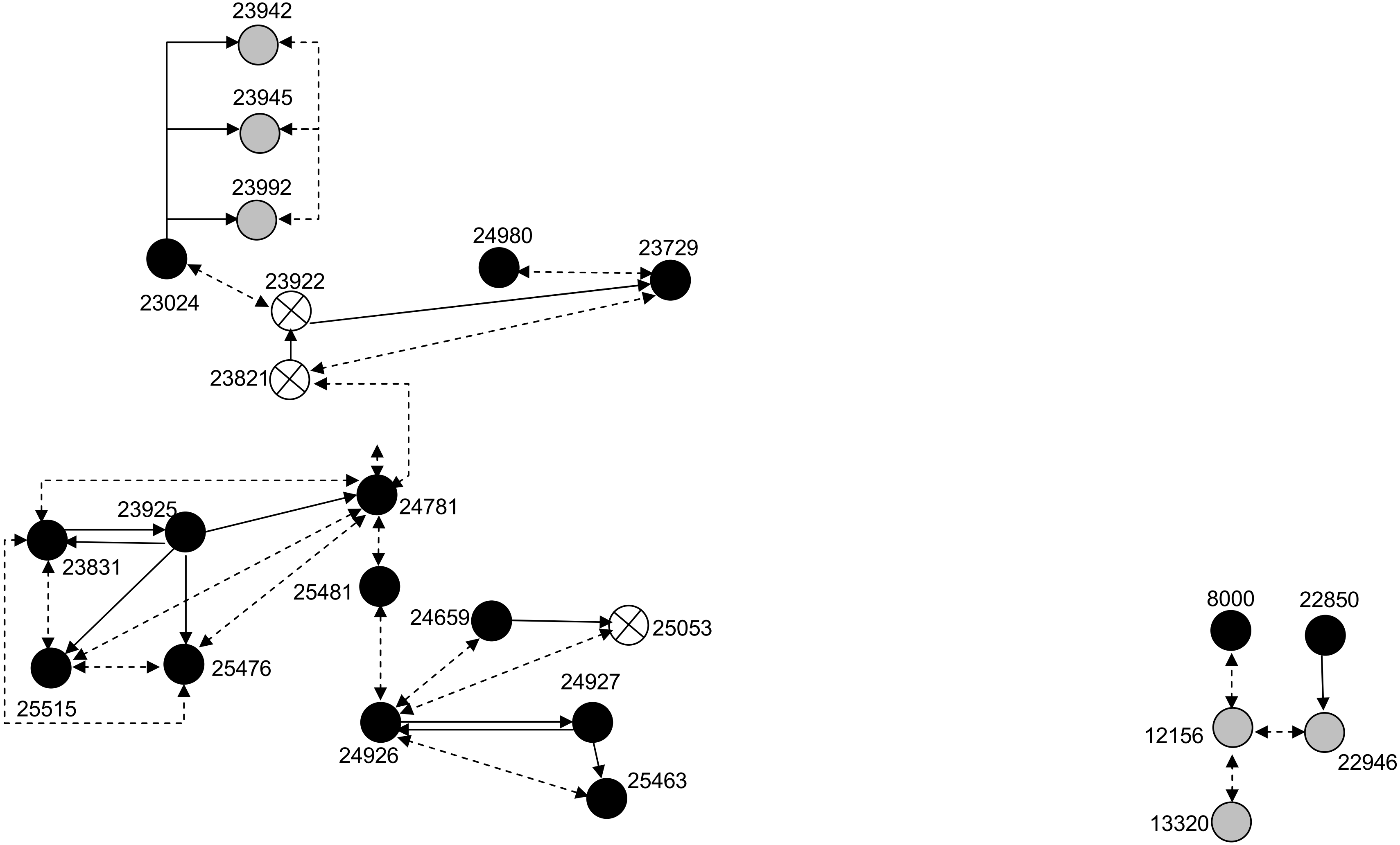
1: Y5 new CRs
ID 1-22000

Analysis of 87CR Network

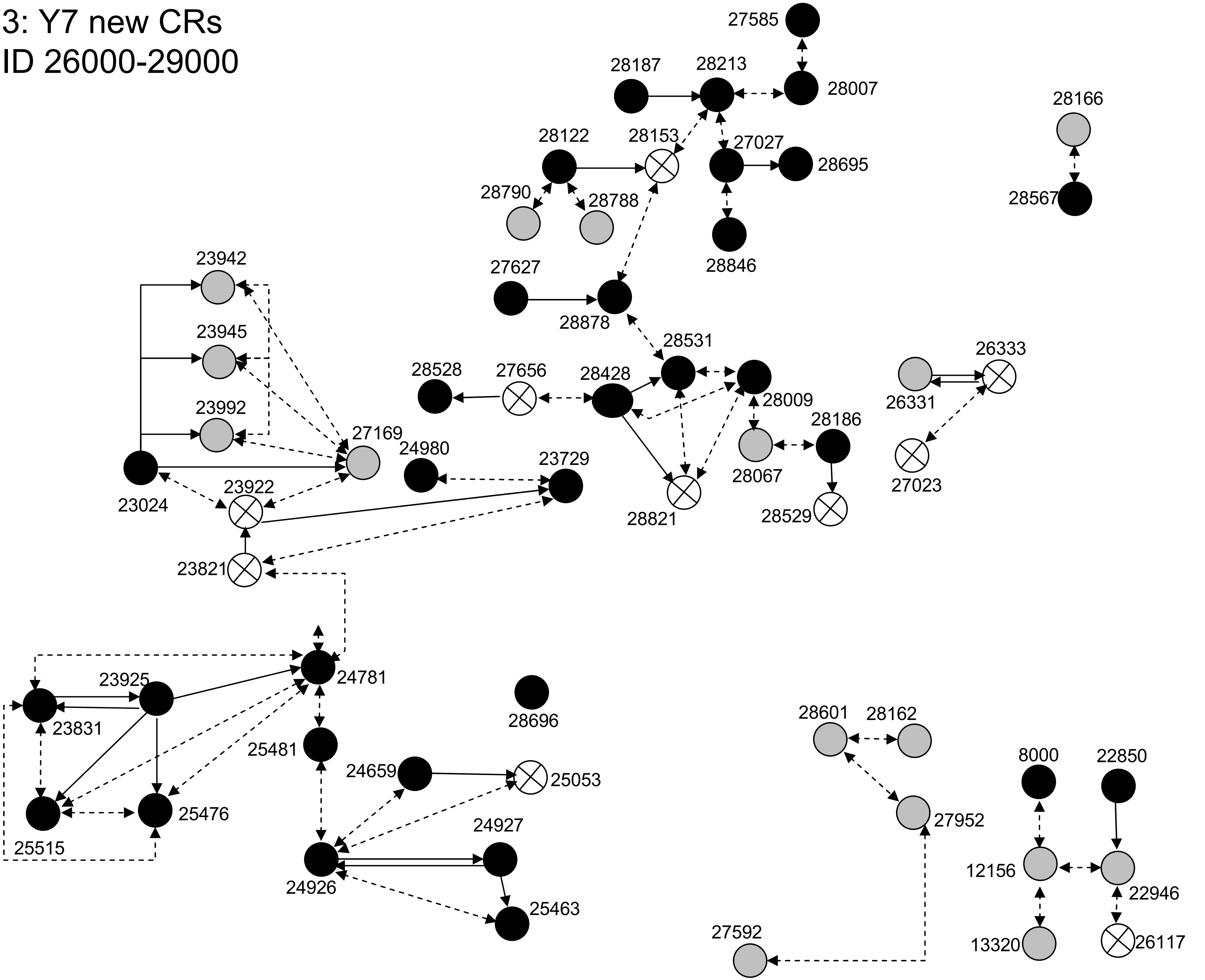




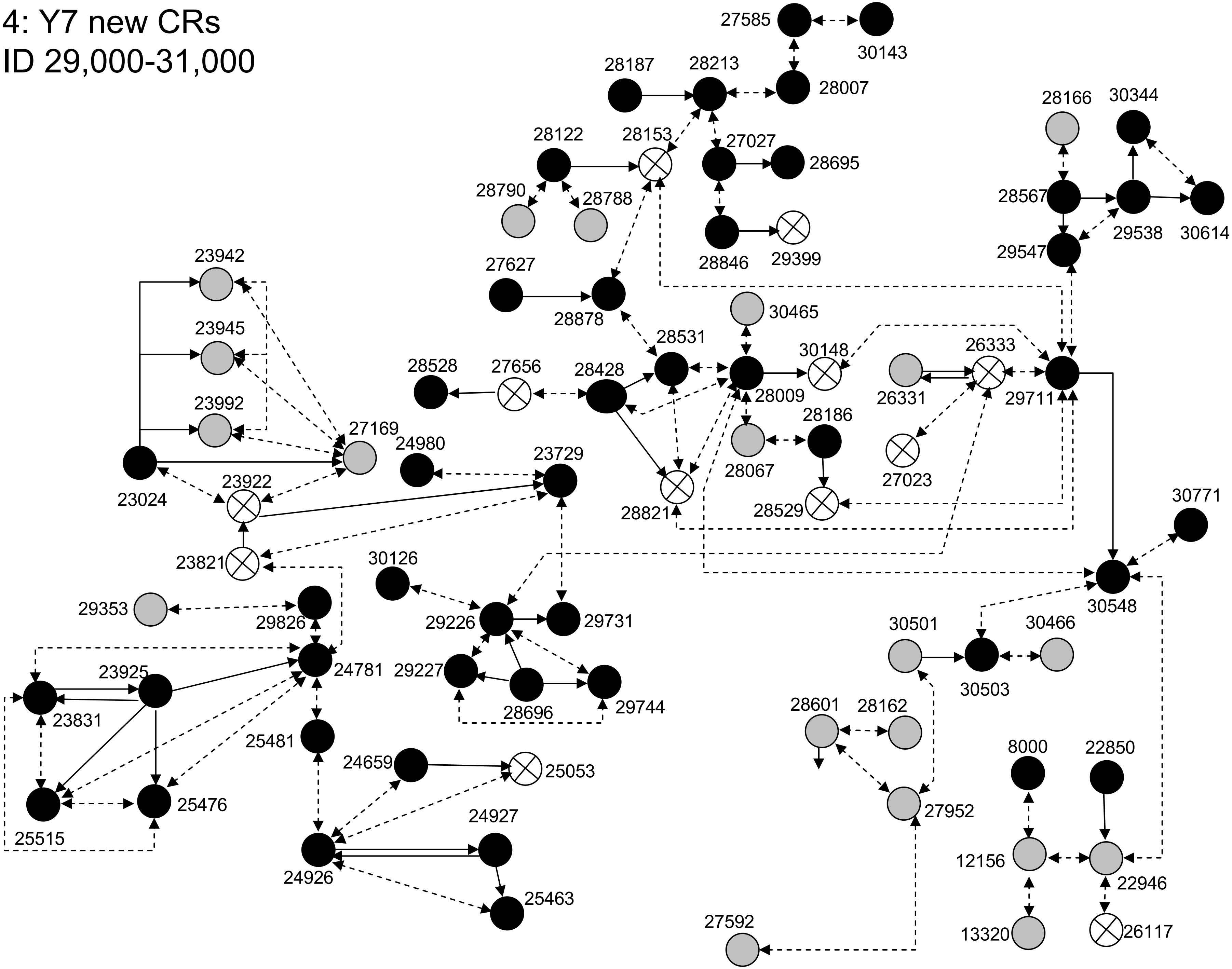
2: Y6 new CRs
ID 22000-26000



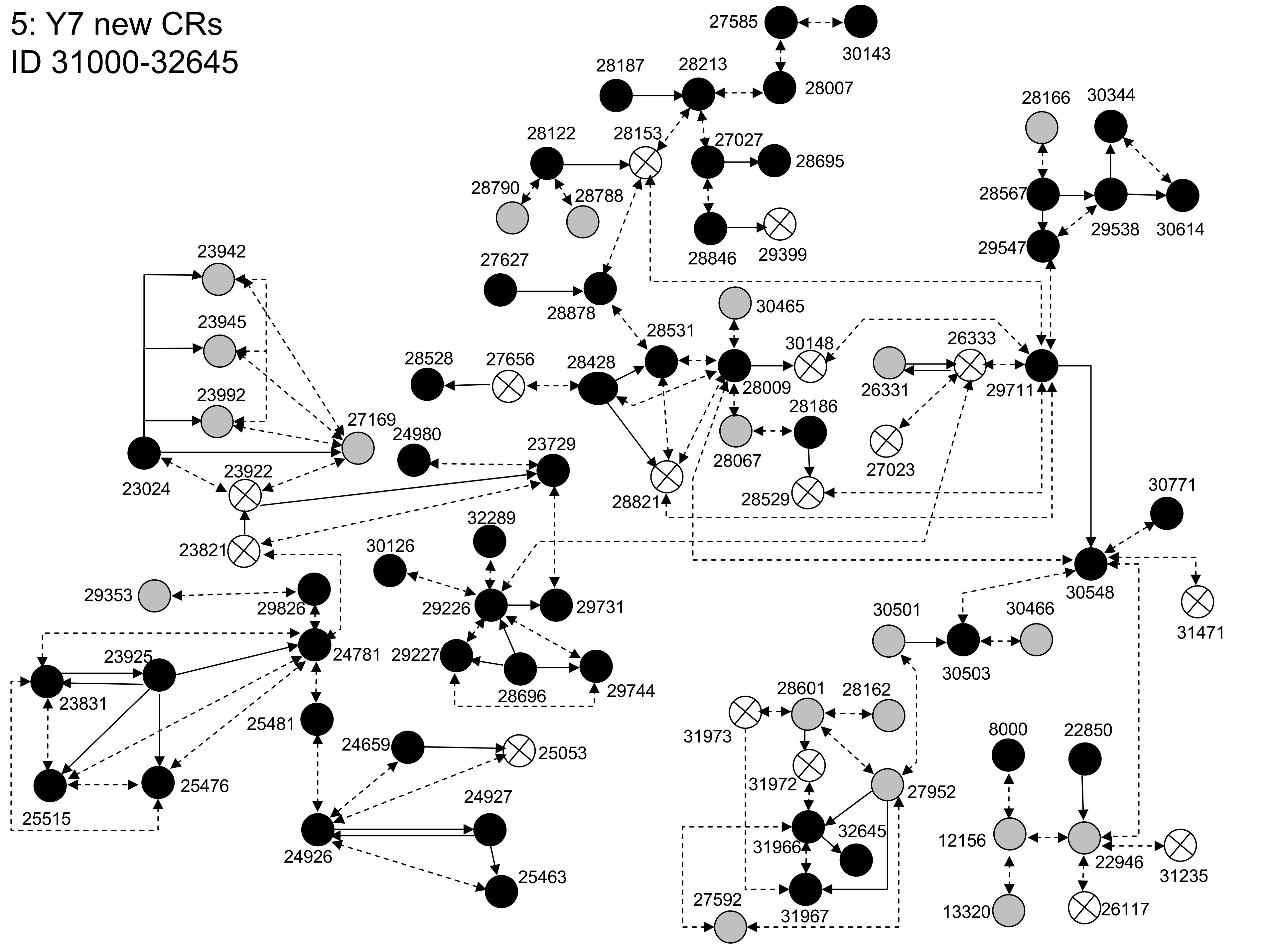
3: Y7 new CRs
ID 26000-29000



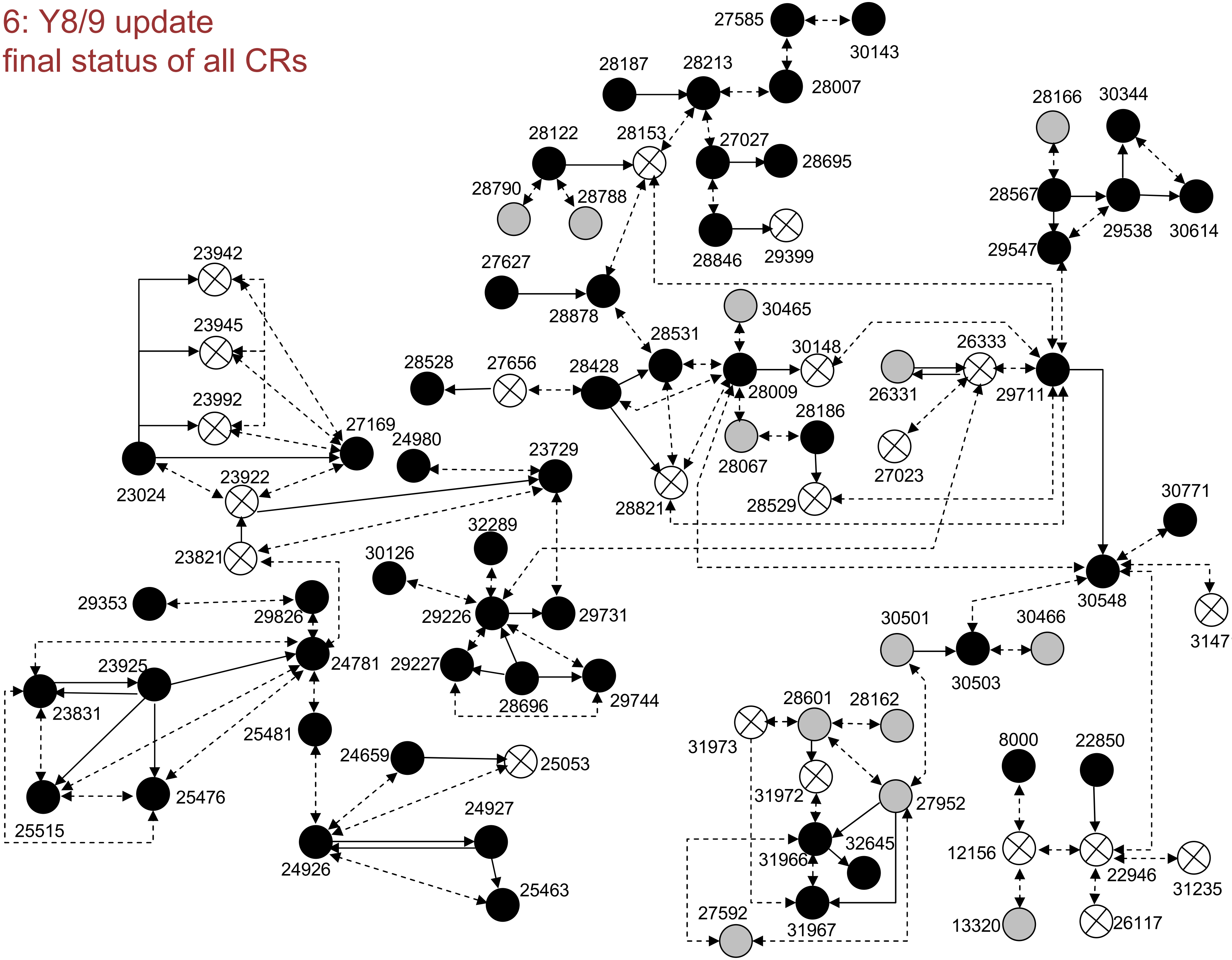
4: Y7 new CRs
ID 29,000-31,000



5: Y7 new CRs
ID 31000-32645



6: Y8/9 update final status of all CRs



Observations

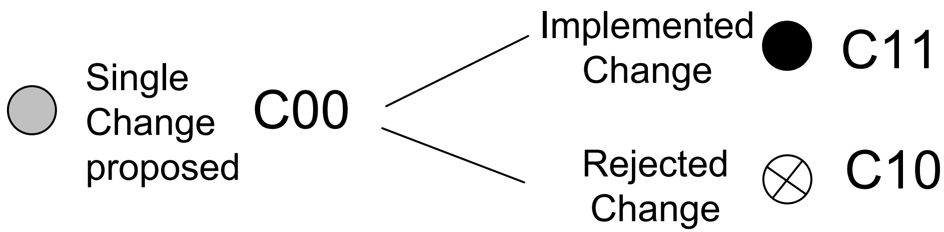
- The 87CR network did not initiate with a single CR and then grow gradually by change propagation
- Several initially unrelated changes grew together to form a larger network over time
- A few changes are highly connected
  - Examples: 24781(7), 29226 (7), 28009 (7)
  - highly connected changes are not necessarily parent changes
- Most changes only connect to one or two other changes

Change Propagation Motifs

Step i   Step j

1-motifs

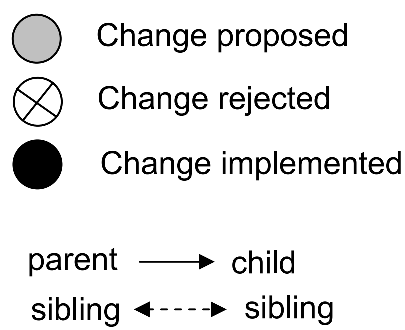
Single Change proposed



1 motifs

Motif	#	%
C00	13	15
C10	21	24
C11	53	61
Total	**87**	**100**

Legend



Observations from 1-motifs

- A majority of proposed changes (61%) is implemented
- About 1 out of every 4 changes is disapproved (25%)
- The status of about 1 in 6 proposed changes remains open (15%), even at the end of the program
  - probably not implemented
- Results for **all** change requests in database

Total # nodes: 41551

isolates: 26125 – 63%
non-isolates: 15426 – 37%

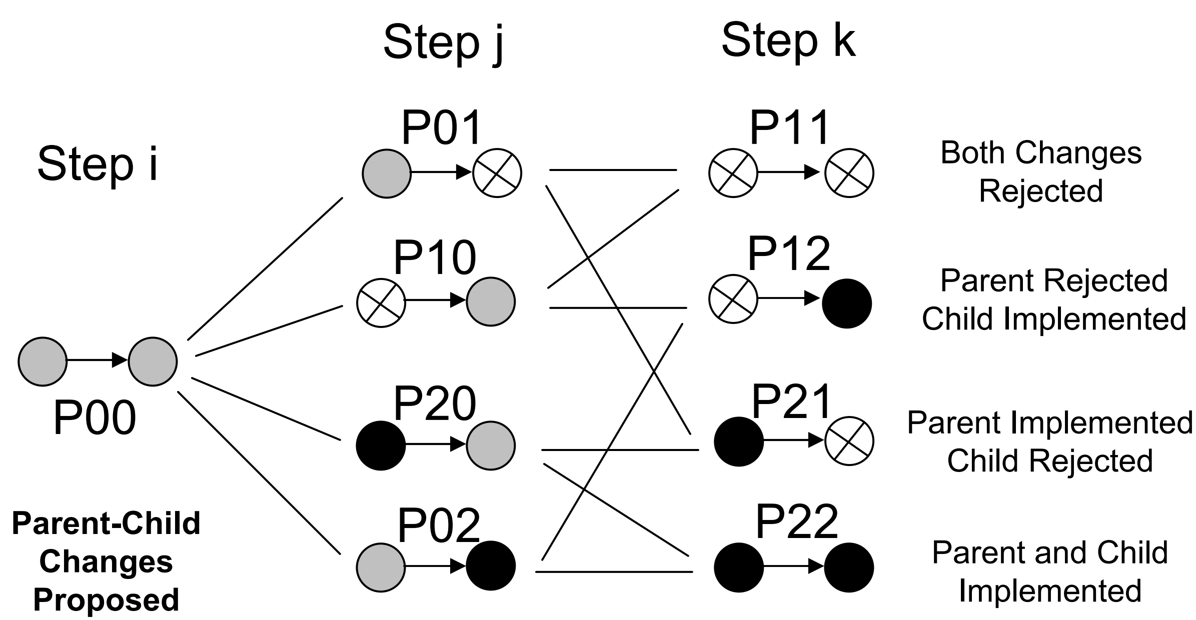
Among isolates:
Proposed: 14153: 54%
Implemented: 9680: 37%
Rejected: 2292 9%

Among nodes in connected components (with nodal degree at least 1):
Proposed: 1458: 9%
Implemented: 10326: 67%
Rejected: 3642: 24%

For entire dataset:
Proposed: 15611: 38%
Implemented: 20006: 48%
Rejected: 5934: 14%

Change Propagation Motifs (cont.)

parent-child-2-motifs



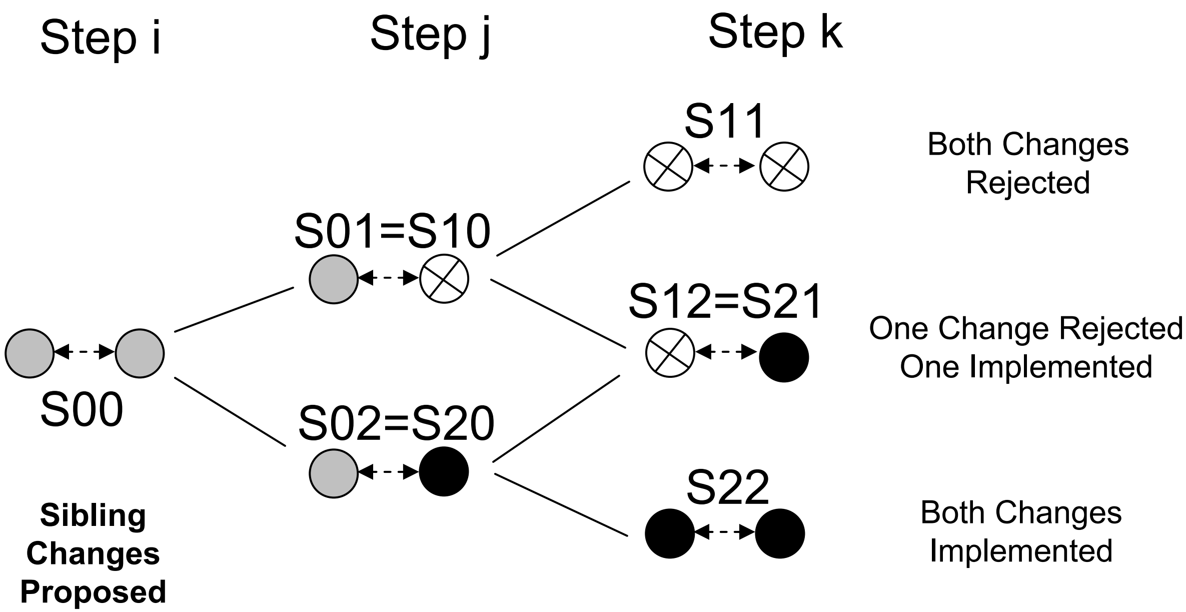
9 unique 2P-motifs
8 possible paths

Analysis of 87CR

Motif	#	%
P00	0	0
P01	2	5
P10	1	2.5
P20	0	0
P02	2	5
P11	1	2.5
P12	1	2.5
P21	9	24
P22	22	58
Total	38	100

Change Propagation Motifs (cont.)

sibling-2-motifs



Analysis of 87CR

Motif	#	%
S00	4	6
S01	2	3
S02	8	12
S11	7	10
S12	19	28
S22	28	41
Total	68	100

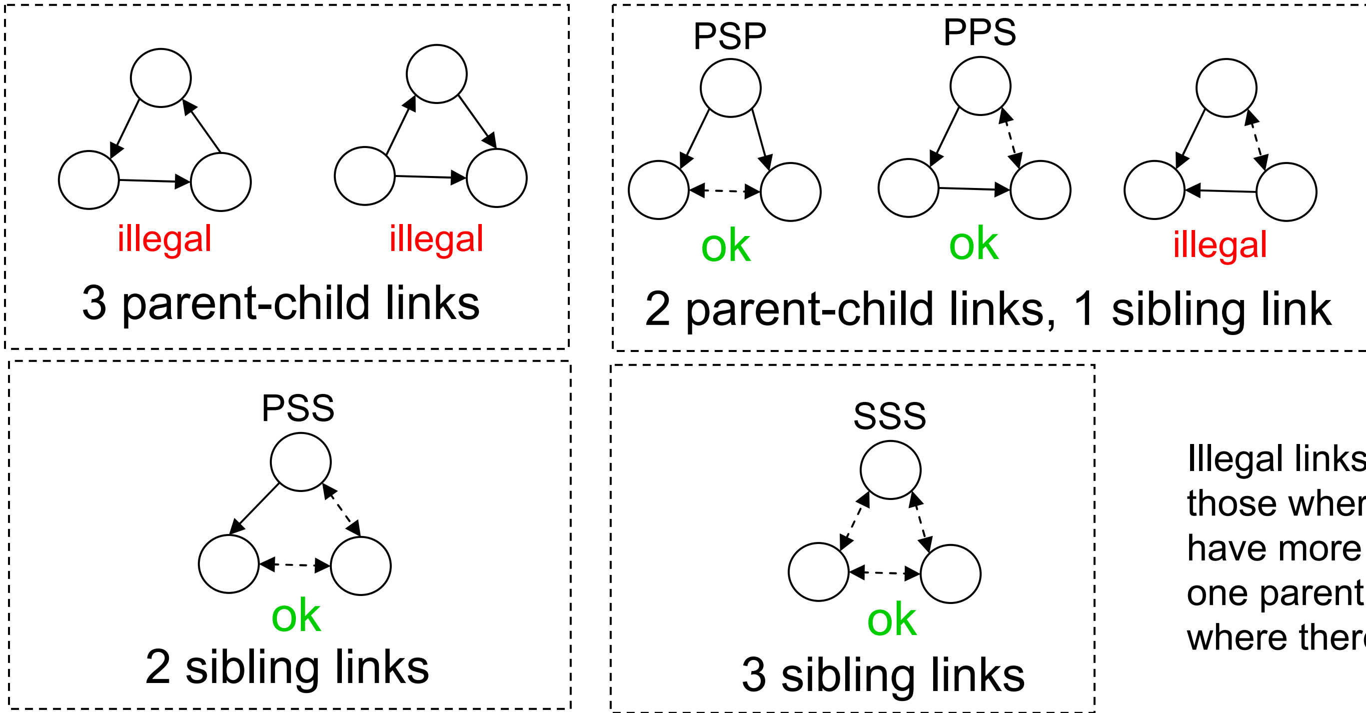
6 unique 2S-motifs
4 possible paths

Observations from 2-motifs

- Parent-Child Pairs
  - The most frequent pattern is that both a parent and child change are implemented as planned (58%)
  - If a change in a change-pair is disapproved it is more likely to be the child (24%)
- Sibling Pairs
  - In sibling pairs it is most likely that both will be implemented (41%) or at least one of them is implemented, while the other one is rejected (28%)
  - If one change in a pair is disapproved there is a 25% chance that the sibling will be disapproved as well

3-motifs

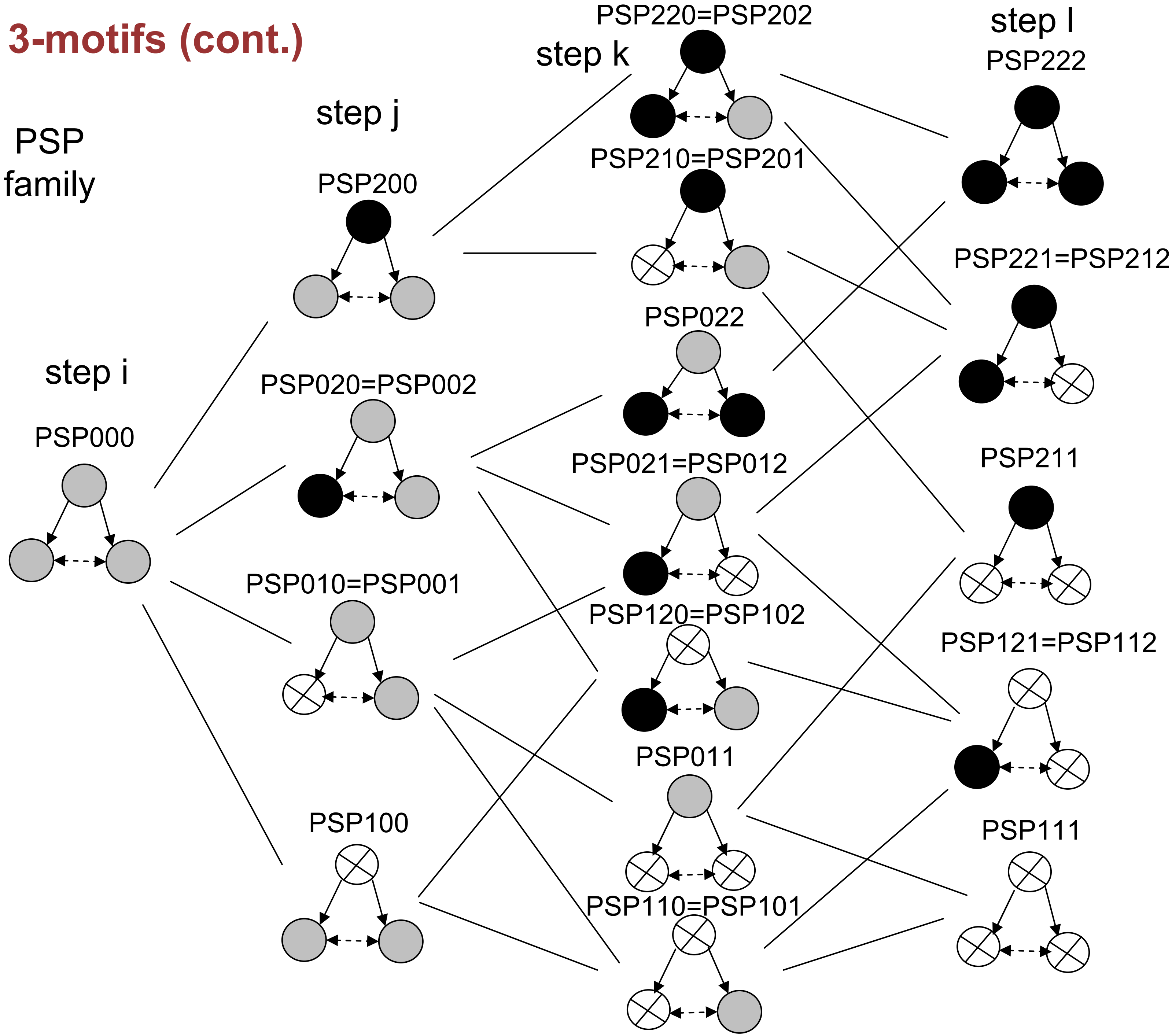
nodal CR connectivity motifs



Illegal links are those where CRs have more than one parent or where there is a cycle

For each legal triplet we can define a set of 3-motifs

3-motifs (cont.)



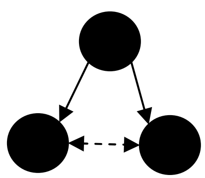
3-motif PSP statistics

PSP family

- Only found two 3-motifs from PSP family to ever occur in 87CR data set

"change family pattern"

PSP222

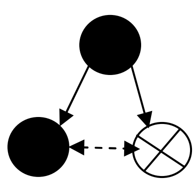


parent and two related child changes were proposed; all were implemented

7 instances found

"change substitution pattern"

PSP221=PSP212



parent and two related child changes were proposed; only one child was implemented

4 instances found

one interpretation: one child change substitutes for another

Observations from 3-motif analysis

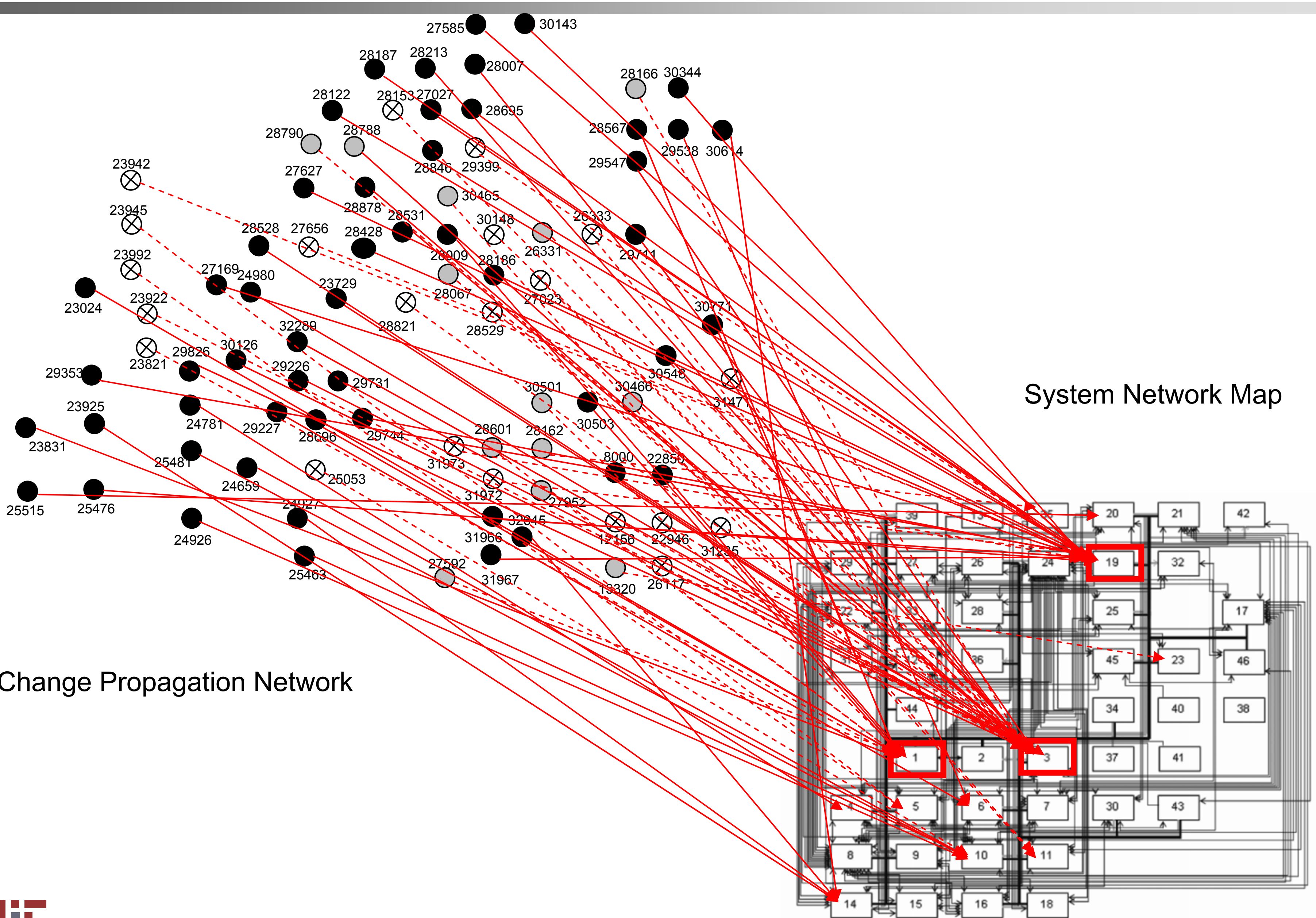
- 3-Motifs give potentially the most insight into the relationship between change requests
- 3-Motifs are not uniformly present
- The most common 3-motifs are:
  - PSP222: Parent + 2 child changes implemented as proposed
  - PSP221: Parent child implemented, one child change rejected and substituted for another
    - potential explanation: as change magnitude/invasiveness is assessed a change is rejected, and a change with equivalent outcome, but applied to another area is substituted
- None of the 3-change motifs found contained any unresolved (open) change requests
  - Open change requests tend to be orphans

[Note: 3-motif analysis for entire dataset still ongoing]

Bi-Partite Graph Analysis

- Bi-partite graph analysis:
  - Analyze relationship of change request network to underlying system area network
- Questions:
  - Which areas are most affected by changes?
  - Which areas are unaffected? [constants]
  - Which areas act as change multipliers, carriers, absorbers?
  - Which areas act as reflectors of change?

1-motif-area-impact analysis



1-motif-area-impact analysis: Results by Area

- Change Activity by area
  - Areas 3, 19 and 1 are most active in terms of number of proposed CR
- Change Acceptance Index (CAI)
  - fraction of proposed changes that are actually implemented
- Change Reflection Index (CRI)
  - fraction of proposed changes that are rejected

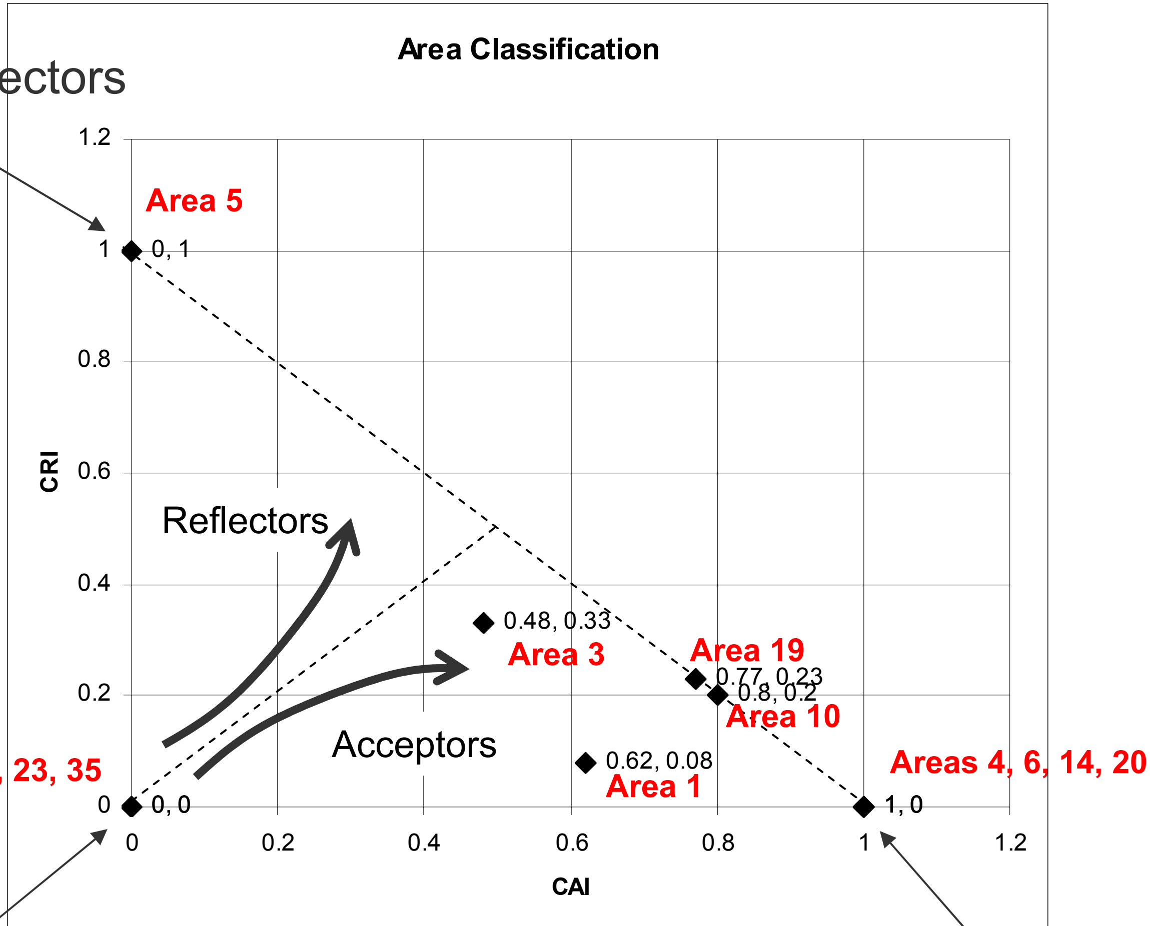
Area	CR	yes	no	open	CAI	CRI
1	13	8	1	4	.62	.08
3	33	16	11	6	.48	.33
4	1	1	0	0	1.0	0.0
5	2	0	2	0	0.0	1.0
6	2	2	0	0	1.0	0.0
10	5	4	1	0	0.8	0.2
11	2	0	0	2	0.0	0.0
14	4	4	0	0	1.0	0.0
19	22	17	5	0	.77	.23
20	1	1	0	0	1.0	0.0
23	1	0	0	1	0.0	0.0
35	1	0	0	1	0.0	0.0
Sum	87	53	20	14	-	-

$$CAI_i = \frac{\text{total number of implemented changes in Area i}}{\text{total number of changes originally proposed in Area i}}$$

$$CRI_i = \frac{\text{total number of rejected changes in Area i}}{\text{total number of changes originally proposed in Area i}}$$

87CR-area classification

perfect reflectors



no CRs issued
or all CR's unresolved

perfect acceptors

Change Propagation Index (CPI)

- Classify each area
  - Absorber, Carrier, Multiplier

change propagation probability

$$p_{ij} = \frac{\sum c_{ij}(parent) + \sum c_{ij}(sibling)}{C_{tot}(j)}$$

total completed changes in Area j

instigating area

ΔDSM Change Propagation Frequency

Area	1	2	3	4	5	6
1	0.4843	0.0011	0.0136	0.0057	0.0125	0.0023
2	0.0061	0.0000	0.0000	0.0030	0.0000	0.0000
3	0.0173	0.0000	0.1053	0.0050	0.0012	0.0000
4	0.0224	0.0000	0.0112	0.0449	0.0000	0.0000
5	0.0137	0.0000	0.0000	0.0000	0.1262	0.0000
6	0.0417	0.0000	0.0000	0.0000	0.0000	0.0833

receiving area

$$C_{in}(i) = \sum_{j=1}^{N} \left(p_{ij} \times C_{tot}(j) \right)$$

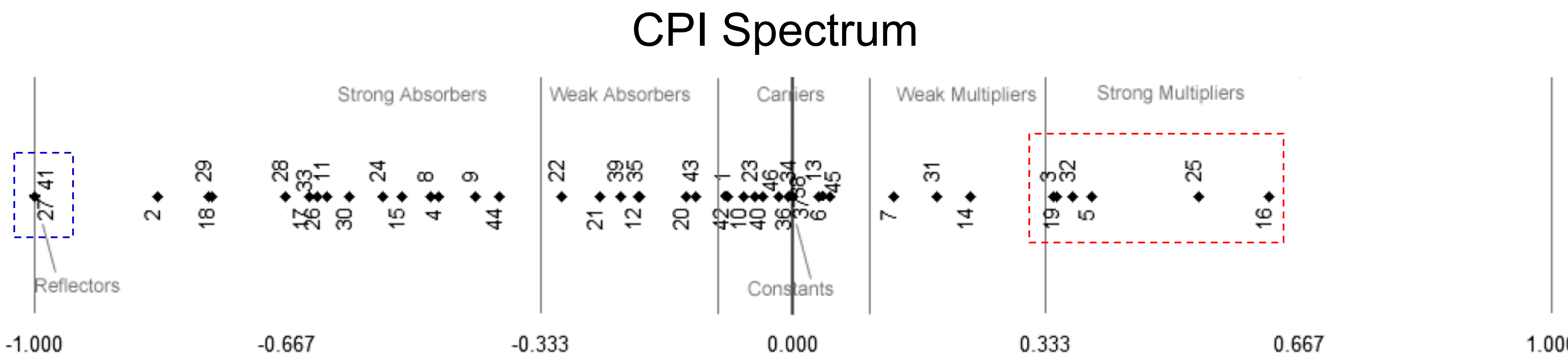
A change in Area 1 caused changes in Area 6 with a frequency of 4.17%.

$$C_{out}(i) = \sum_{j=1}^{N} \left(p_{ji} \times C_{tot}(i) \right)$$

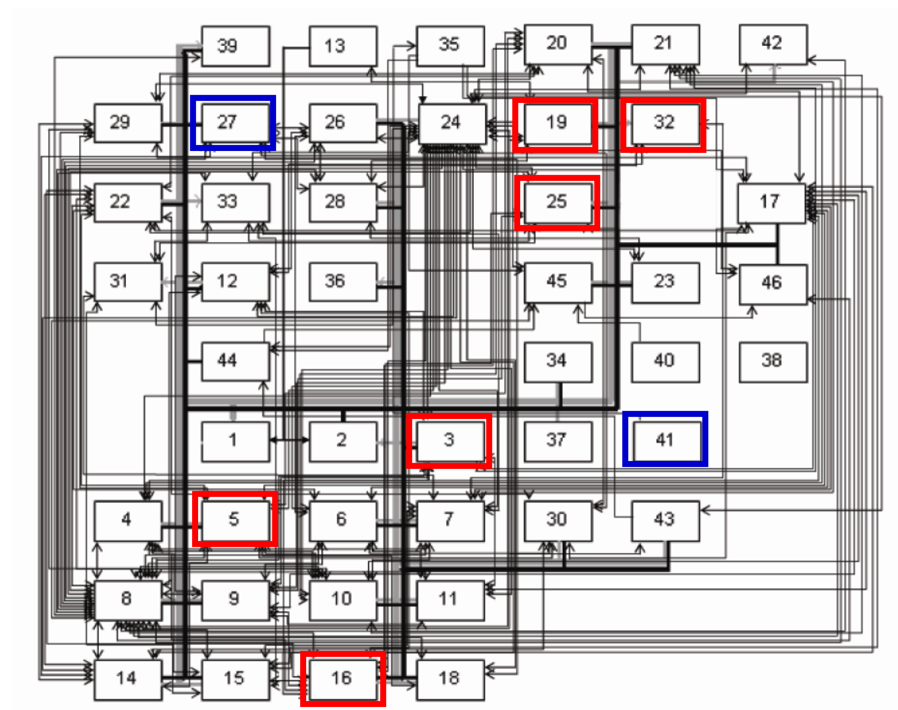
$$CPI(i) = \frac{C_{out}(i) - C_{in}(i)}{C_{out}(i) + C_{in}(i)}$$

-1 <= CPI <= +1

System Area Classification



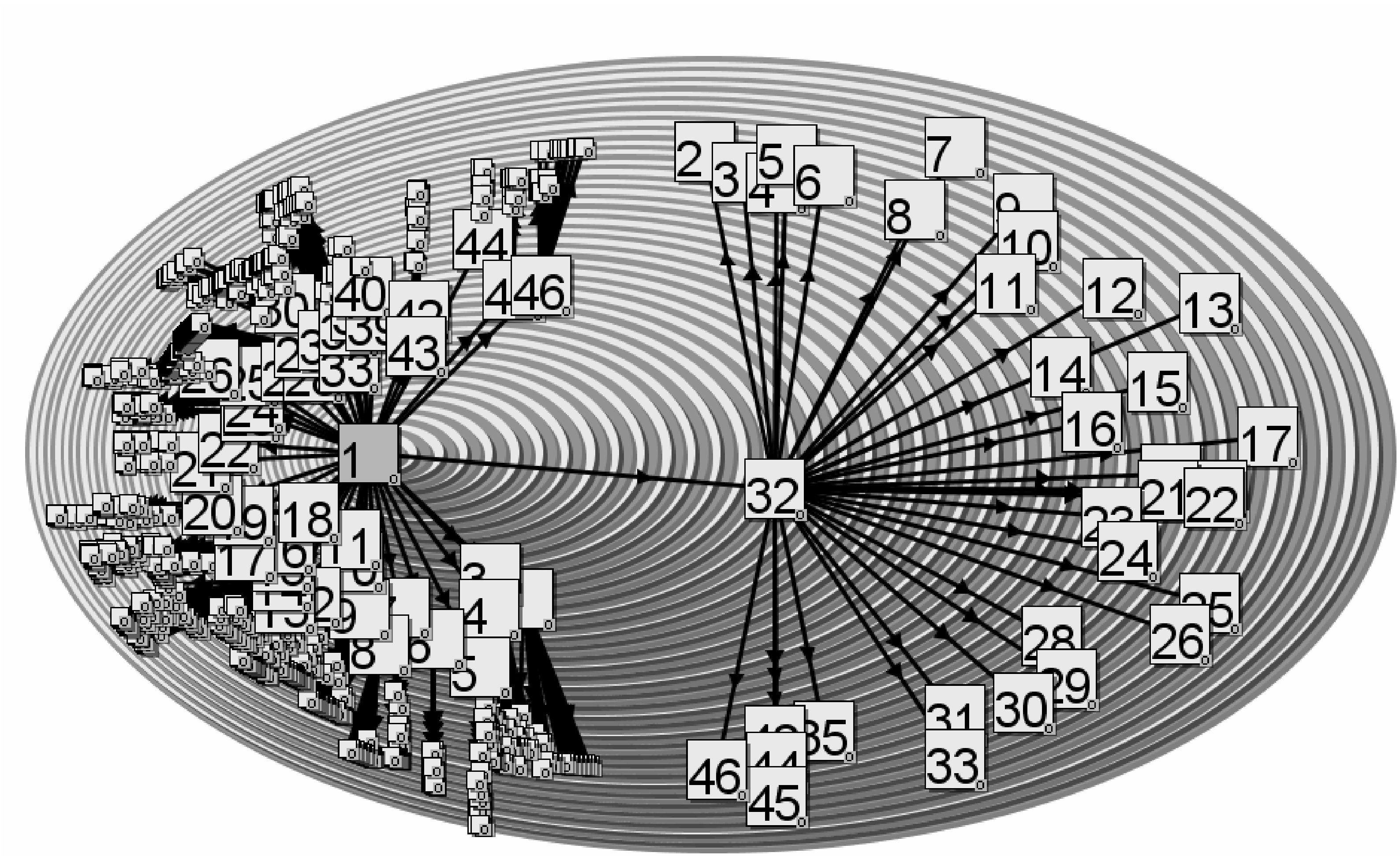
- Areas found to be strong multipliers
  - 16: hardware performance evaluation
  - 25: hardware functional evaluation
  - 5: core data processing logic
  - 32: system evaluation tools
  - 19: common software services
  - 3: graphical user interface (GUI)
- Areas found to be perfect reflectors
  - 27, 41: look like perfect absorbers
  - but actually zero changes implemented
  - despite numerous changes proposed
  - = perfect reflectors



Massachusetts Institute of Technology

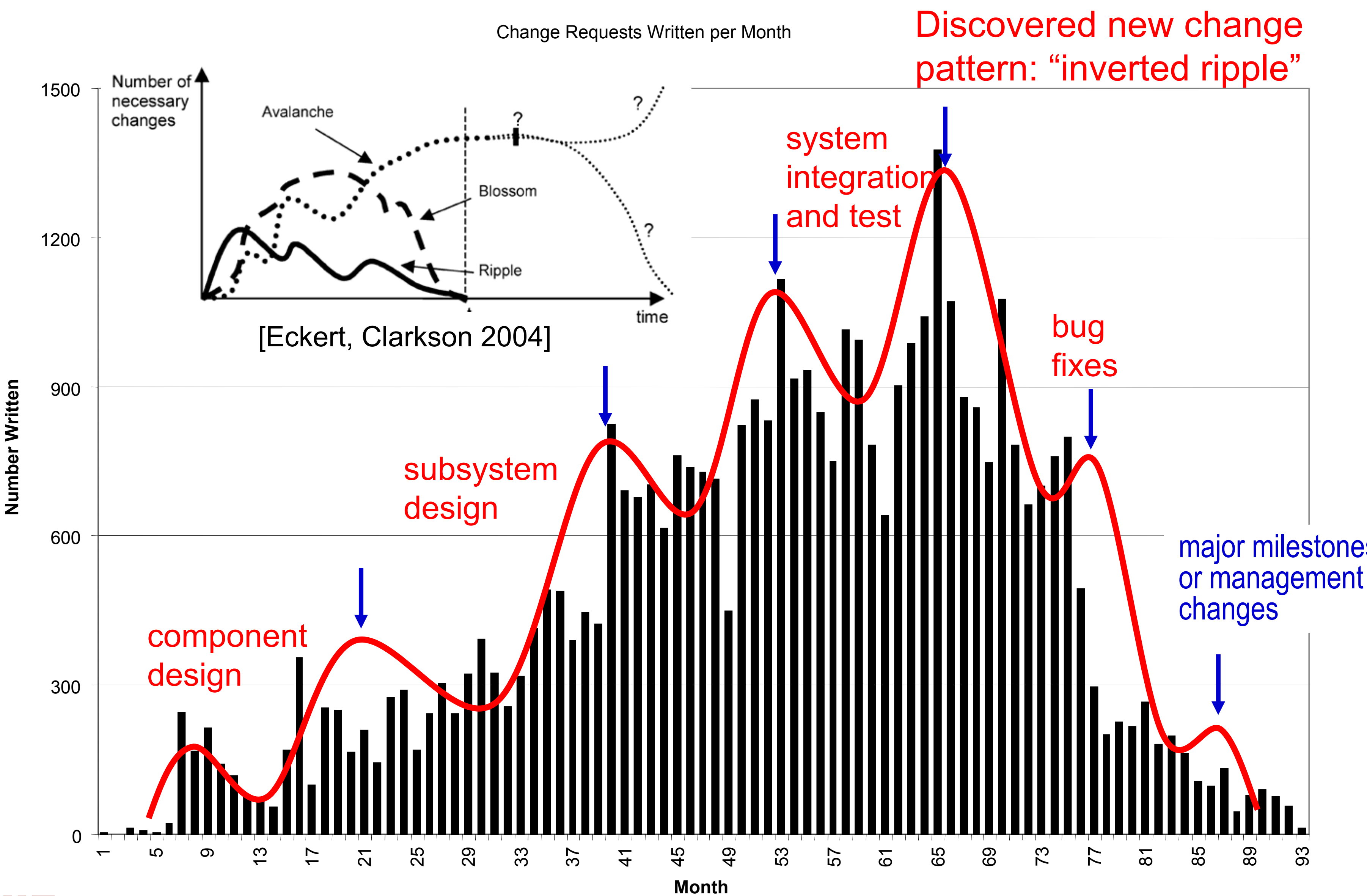
CPM Visualization Tool

- Developed at EDC, University of Cambridge, UK



Likelihood of changes propagating from area 1 to other areas

Change Request Generation



Discussion and Future Work

Conclusions

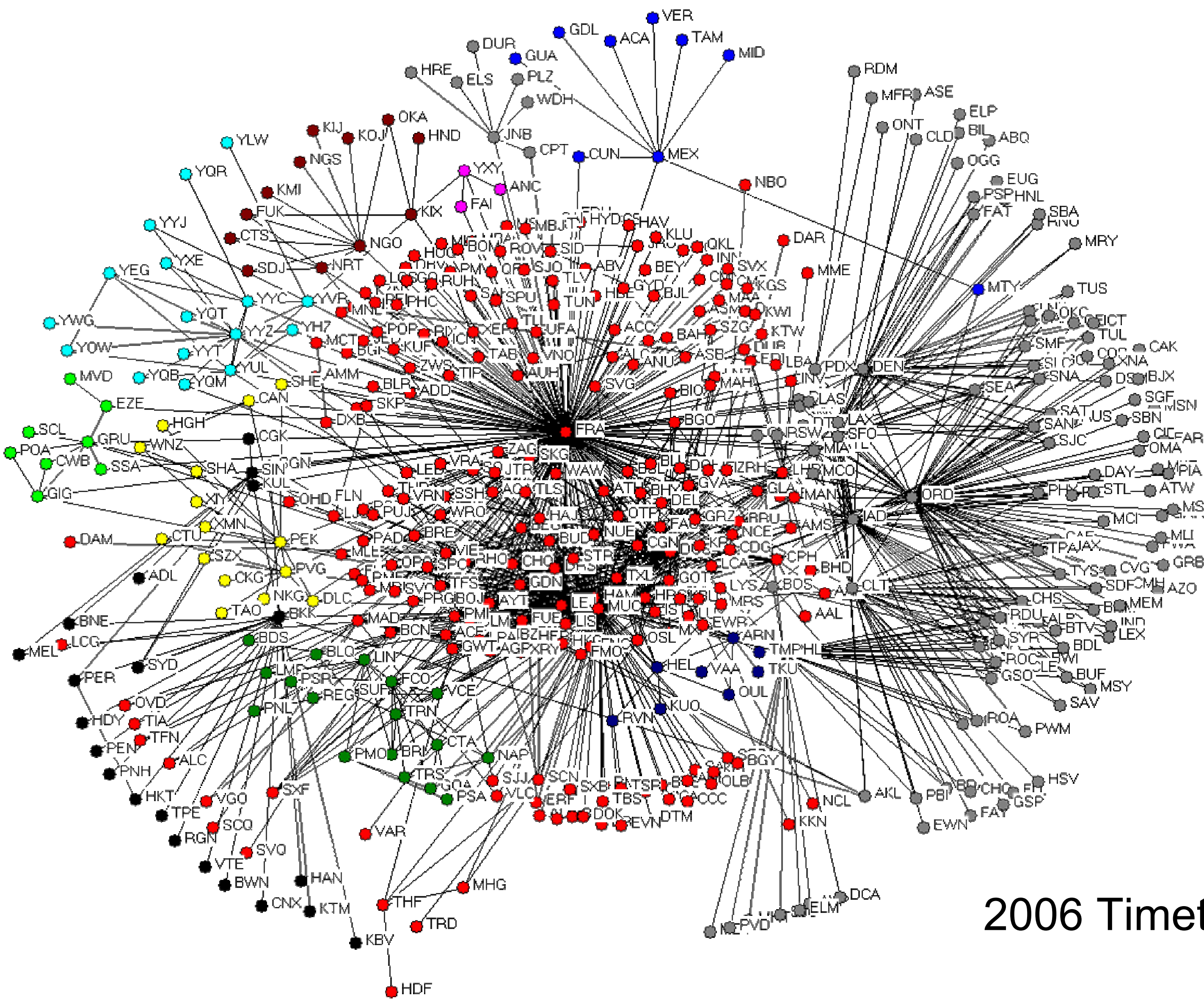
- Change propagation is a consistent occurrence in the development of complex technical systems.
- Change activity was not uniformly distributed throughout the system but more concentrated in some areas: 1, 3, 16, 19 and 32.
- A small number of areas that involved more than 10 implemented changes acted as strong multipliers (CPI>0.3).

A-posteriori analysis of change propagation can be used to estimate likelihood and impact magnitude of future system design efforts.

Future Work - Discussion

- Change propagation in complex systems
  - refine CPI
    - sibling changes: count them or not?
  - how to best use change magnitude
  - compare predicted versus actual change propagation and effort
- Tri-partite graph analysis:
  - System network, Task network, Organizational network
- Empirical/Theoretical work on system evolution over time
  - Whitney: subway evolution study
  - Bounova: evolution of airline networks

Lufthansa Air Transportation Network



2006 Timetable

More Information

- Thinking about complex systems engineering design in terms of <u>change over time</u> is important when we face:
  - long lifecycles
  - exogenous uncertainty
  - large, (partially) irreversible investments

- http://strategic.mit.edu