OPTIMIZING CHANNELIZATION FOR FUN AND PROFIT

Or: How I Learned to Stop Worrying and Love the Multiplexer

PREPARED FOR RAMS TRAINING SUMMIT XIII

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WHAT'S THE BOTTOM LINE?

Design for reliability by using your multiplexer's un-assigned channels.

With optimal channelization, software can detect, correct, and eliminate critical outcomes due to addressing failures.

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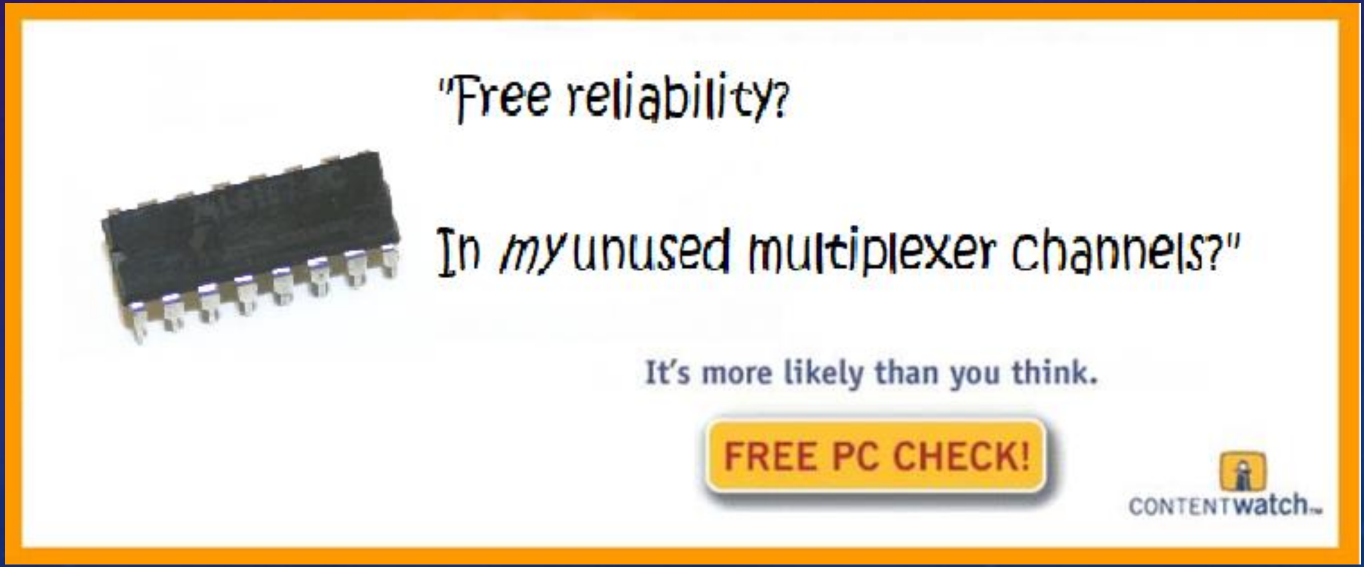

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Reliability: The probability that a system will perform its intended function adequately for a specified period of time.

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Multiplexer: A EEE device which selects between several input signals and forwards one (1) selected signal to output. (Also known as a data selector or MUX)

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Un-assigned Channel: A MUX's input signal which has no sensor or device attached. Un-assigned channels output GND or 0 V when selected. (channels 5-7 in example)

8 to 1 MUX	
Channel	Sensor
0	Pressure Sensor 1
1	Pressure Sensor 2
2	5V Voltage Reference
3	Temp. Sensor 1
4	Temp. Sensor 2
5	N/A
6	N/A
7	N/A

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Channelization: The order in which sensors/signals are connected to the MUX inputs

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1	Pressure Sensor 2
2	5V Voltage Reference
3	Temp. Sensor 1
4	Temp. Sensor 2
5	N/A
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7	N/A

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Addressing Failure: a failure in the software, logic circuit, or MUX itself which causes the wrong channel to be requested or transmitted.

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WANT →

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0	Pressure Sensor 1
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GET

8 to 1 MUX	
Channel	Sensor
0	Pressure Sensor 1
1	Pressure Sensor 2
2	5V Voltage Reference
3	Temp. Sensor 1
4	Temp. Sensor 2
5	N/A
6	N/A
7	N/A

ADDRESSING FAILURE MECHANICS

A MUX uses digital 'select lines' to control which input is sent to output. In an 8 to 1 MUX (see right), there are 3 select lines. Select digits form the channel # in binary.

An addressing failure most often occurs at the level of an Integrated Chip, when an open, short, or instantaneous discharge causes one of these select lines (A2, A1, or A0) to be stuck high or low.

8 to 1 MUX				
Channel	A2	A1	A0	Sensor
0	0	0	0	Pressure Sensor 1
1	0	0	1	Pressure Sensor 2
2	0	1	0	5V Voltage Reference
3	0	1	1	Temp. Sensor 1
4	1	0	0	Temp. Sensor 2
5	1	0	1	N/A
6	1	1	0	N/A
7	1	1	1	N/A

ADDRESSING FAILURE MECHANICS - EXAMPLE

Consider an electrical short in the IC which causes A2 to be stuck ‘high’ (always have logic ‘1’, regardless of command).

Expected					Received				
Channel	A2	A1	A0		Channel	A2	A1	A0	
0	0	0	0	Pressure Sensor 1	4	1	0	0	Temp. Sensor2
1	0	0	1	Pressure Sensor 2	5	1	0	1	N/A
2	0	1	0	5V Voltage Reference	6	1	1	0	N/A
3	0	1	1	Temp. Sensor 1	7	1	1	1	N/A
4	1	0	0	Temp. Sensor2	4	1	0	0	Temp. Sensor2
5	1	0	1	N/A	5	1	0	1	N/A
6	1	1	0	N/A	6	1	1	0	N/A
7	1	1	1	N/A	7	1	1	1	N/A

ADDRESSING FAILURE MECHANICS - EXAMPLE

Now, when expecting telemetry from channel 0, values from channel 4 are transmitted instead. When channels 1-3 are expected, the transmitted signal is from channels 5-7 instead. N/A channels output 0V.

Expected					Received				
Channel	A2	A1	A0		Channel	A2	A1	A0	
0	0	0	0	Pressure Sensor 1	4	1	0	0	Temp. Sensor2
1	0	0	1	Pressure Sensor 2	5	1	0	1	N/A
2	0	1	0	5V Voltage Reference	6	1	1	0	N/A
3	0	1	1	Temp. Sensor 1	7	1	1	1	N/A
4	1	0	0	Temp. Sensor2	4	1	0	0	Temp. Sensor2
5	1	0	1	N/A	5	1	0	1	N/A
6	1	1	0	N/A	6	1	1	0	N/A
7	1	1	1	N/A	7	1	1	1	N/A

ADDR[illegible] FAILURE MECHANICS - EXAMPLE

Now, when requesti[illegible] from chann[illegible] from channel 4 are transmitted instead. Whe[illegible] requested, the transmitted signal is from c[illegible] MUX outputs 0 V.

Channe[illegible]									
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]nsor 2	5	1	[illegible]	[illegible]	[illegible]/A
2	0	1	[illegible]	[illegible]ence	[illegible]	[illegible]	1	0	N/A
3	0	1	1	Temp. [illegible]	[illegible]	1	1	1	N/A
4	1	0	[illegible]	[illegible]r2	[illegible]	[illegible]	[illegible]	0	Temp. Sensor2
5	[illegible]	[illegible]	[illegible]	N/A	5	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1	1	0	N/A	6	1	1	0	[illegible]
7	1	1	1	N/A	7	1	1	1	N/A

ADDRESSING FAILURE MECHANICS - EXAMPLE

Consider a launch vehicle using a pressure sensor suite to determine pressure in its propellant tanks. With the wrong information telemetered, the vehicle underestimates the pressure, and software decides to increase it.

Now we have a critical overpressure condition!

Expected					Received				
Channel	A2	A1	A0		Channel	A2	A1	A0	
0	0	0	0	Pressure Sensor 1	4	1	0	0	Temp. Sensor2
1	0	0	1	Pressure Sensor 2	5	1	0	1	N/A
2	0	1	0	5V Voltage Reference	6	1	1	0	N/A
3	0	1	1	Temp. Sensor 1	7	1	1	1	N/A
4	1	0	0	Temp. Sensor2	4	1	0	0	Temp. Sensor2
5	1	0	1	N/A	5	1	0	1	N/A
6	1	1	0	N/A	6	1	1	0	N/A
7	1	1	1	N/A	7	1	1	1	N/A

DETECT THESE ERRORS WITH CHANNELIZATION

Channels 1-3 are now erroneously telemetering data from channels 5-7.

Since these are un-assigned channels, this is a full scale low – 0 Volts.

A full scale low reading can be detected with software and disqualified.

Expected					Received				
Channel	A2	A1	A0		Channel	A2	A1	A0	
0	0	0	0	Pressure Sensor 1	4	1	0	0	Temp. Sensor2
1	0	0	1	Pressure Sensor 2	5	1	0	1	N/A
2	0	1	0	5V Voltage Reference	6	1	1	0	N/A
3	0	1	1	Temp. Sensor 1	7	1	1	1	N/A
4	1	0	0	Temp. Sensor2	4	1	0	0	Temp. Sensor2
5	1	0	1	N/A	5	1	0	1	N/A
6	1	1	0	N/A	6	1	1	0	N/A
7	1	1	1	N/A	7	1	1	1	N/A

DETECT THESE ERRORS WITH CHANNELIZATION

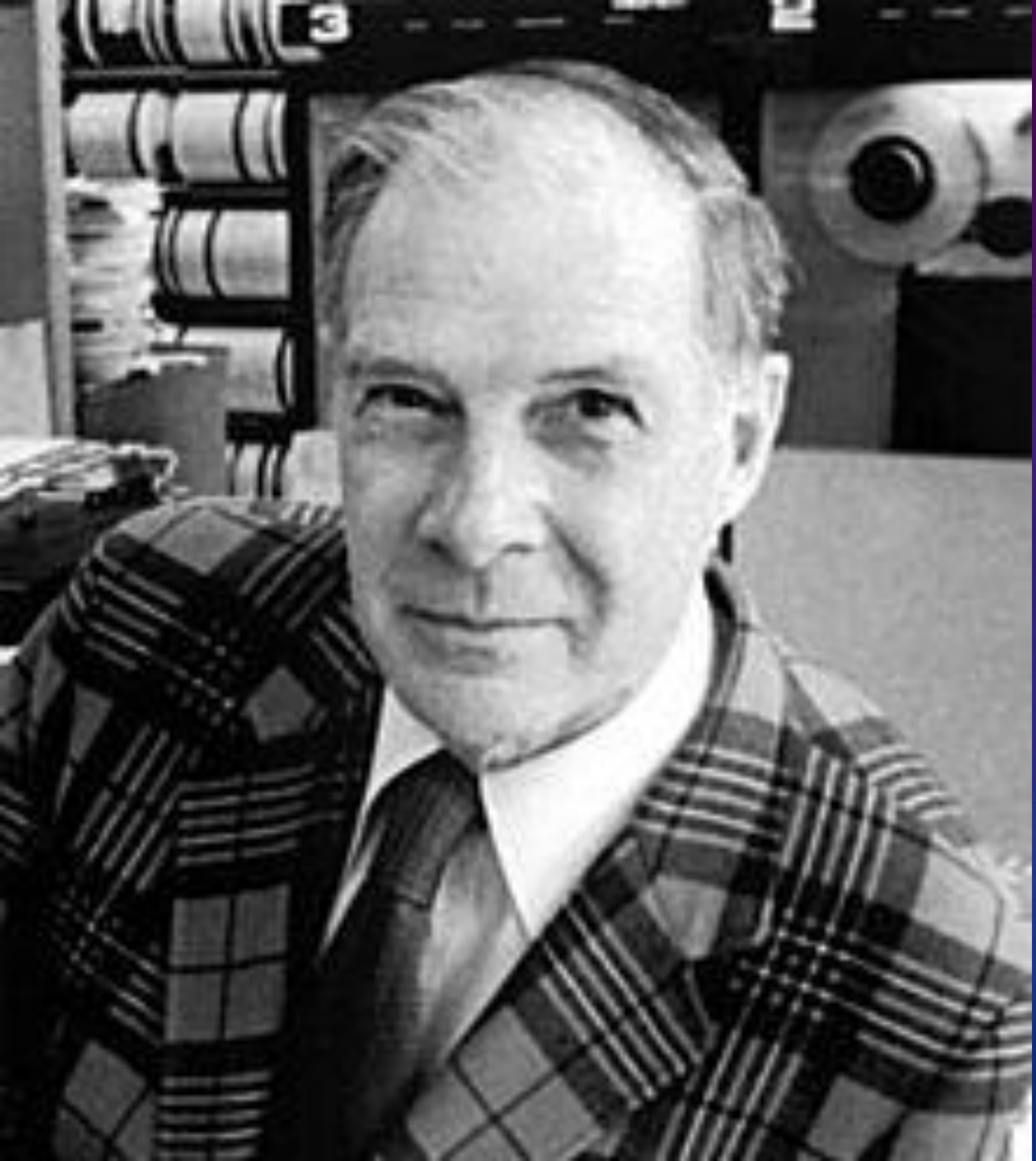
Depending on your product or program's sensor suite and software, this may mean that the erroneous measurement can be detected and excluded from use, or corrected, *before* the failure propagates.

Expected					Received				
Channel	A2	A1	A0		Channel	A2	A1	A0	
0	0	0	0	Pressure Sensor 1	4	1	0	0	Temp. Sensor2
1	0	0	1	Pressure Sensor 2	5	1	0	1	N/A
2	0	1	0	5V Voltage Reference	6	1	1	0	N/A
3	0	1	1	Temp. Sensor 1	7	1	1	1	N/A
4	1	0	0	Temp. Sensor2	4	1	0	0	Temp. Sensor2
5	1	0	1	N/A	5	1	0	1	N/A
6	1	1	0	N/A	6	1	1	0	N/A
7	1	1	1	N/A	7	1	1	1	N/A

DETECT THESE ERRORS WITH CHANNELIZATION

Can we channelize these sensors in such a way that an addressing failure always causes the MUX to telemeter an un-assigned channel?

Expected					Received				
Channel	A2	A1	A0		Channel	A2	A1	A0	
0	0	0	0	Pressure Sensor 1	4	1	0	0	Temp. Sensor2
1	0	0	1	Pressure Sensor 2	5	1	0	1	N/A
2	0	1	0	5V Voltage Reference	6	1	1	0	N/A
3	0	1	1	Temp. Sensor 1	7	1	1	1	N/A
4	1	0	0	Temp. Sensor2	4	1	0	0	Temp. Sensor2
5	1	0	1	N/A	5	1	0	1	N/A
6	1	1	0	N/A	6	1	1	0	N/A
7	1	1	1	N/A	7	1	1	1	N/A



LET'S ASK RICHARD!

- Richard Hamming (1915 – 1998)
- American mathematician
- CPE and Telecom : Hamming code, Hamming window, sphere-packing, Hamming Distance.
- Manhattan Project

"The purpose of computing is insight, not numbers"

Photo : Wikipedia via Bell Labs

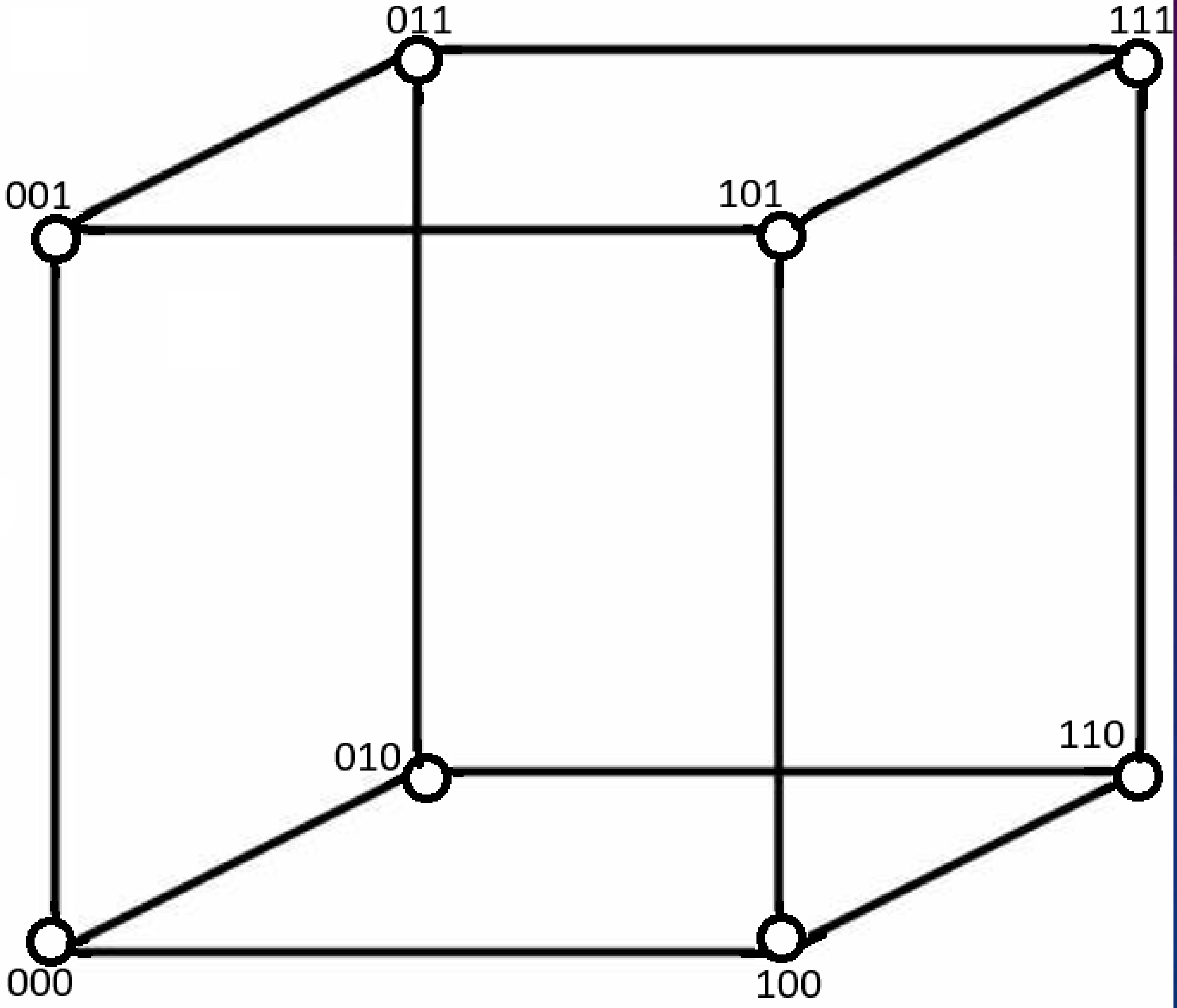
HAMMING DISTANCE

The Hamming Distance between two binary expressions of equal length is the number of bit positions in which the two bits are different.

Expression A			Expression B			Hamming Distance
0	0	0	0	0	0	0
0	0	0	0	1	1	2
0	1	0	1	0	1	3

In an 8-to-1 MUX (3 binary digits), a single addressing failure means that the expected channel could be replaced by **any of the channels within a Hamming Distance of 1.** These channels are called Hamming-Adjacent.

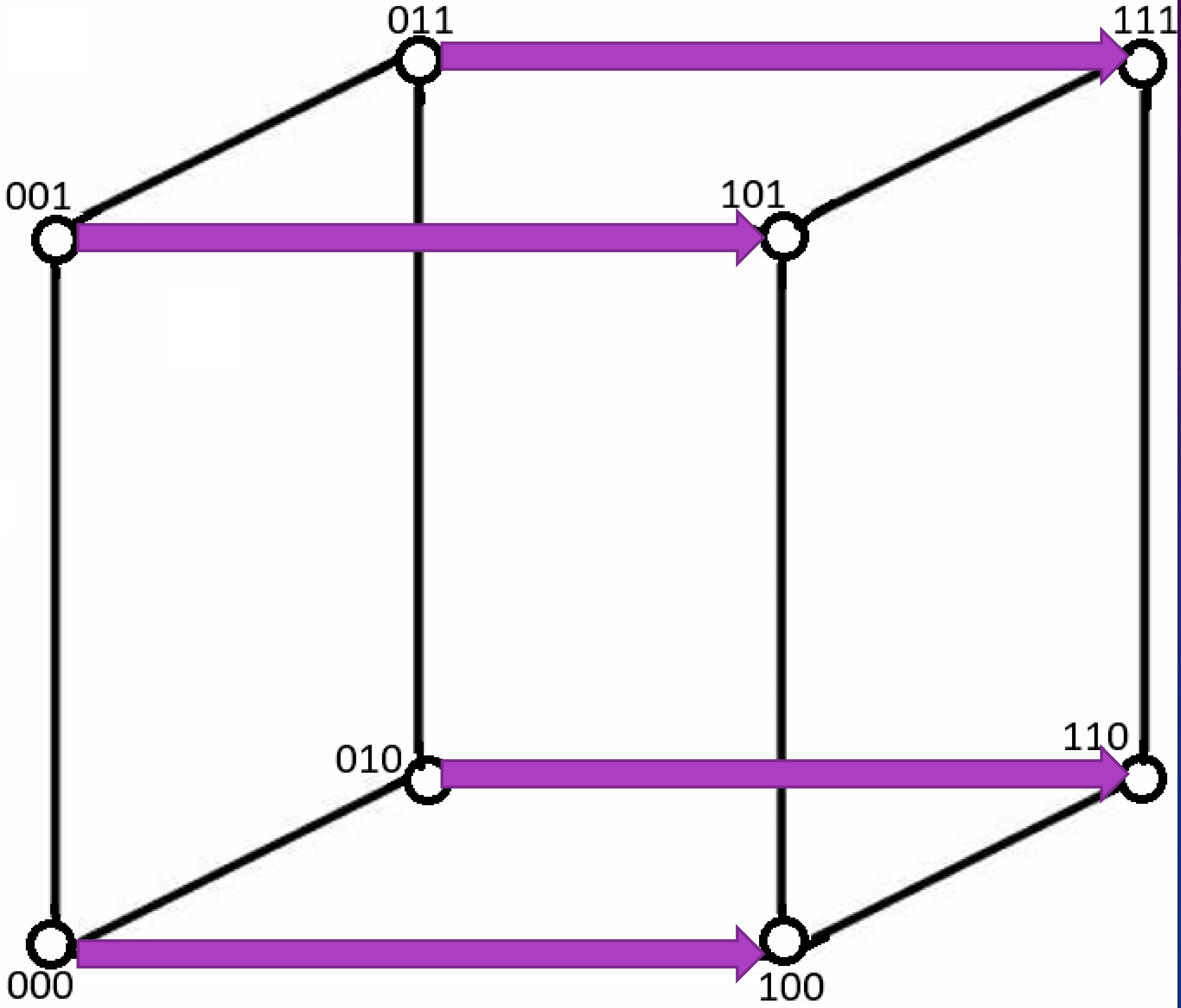
100 -> 000, 110, or 101



HAMMING CUBE
8 POSITIONS

The Hamming Cube is a visual representation of the addressing space of an 8 position MUX.

Each axis is one of the select lines A2, A1, or A0.



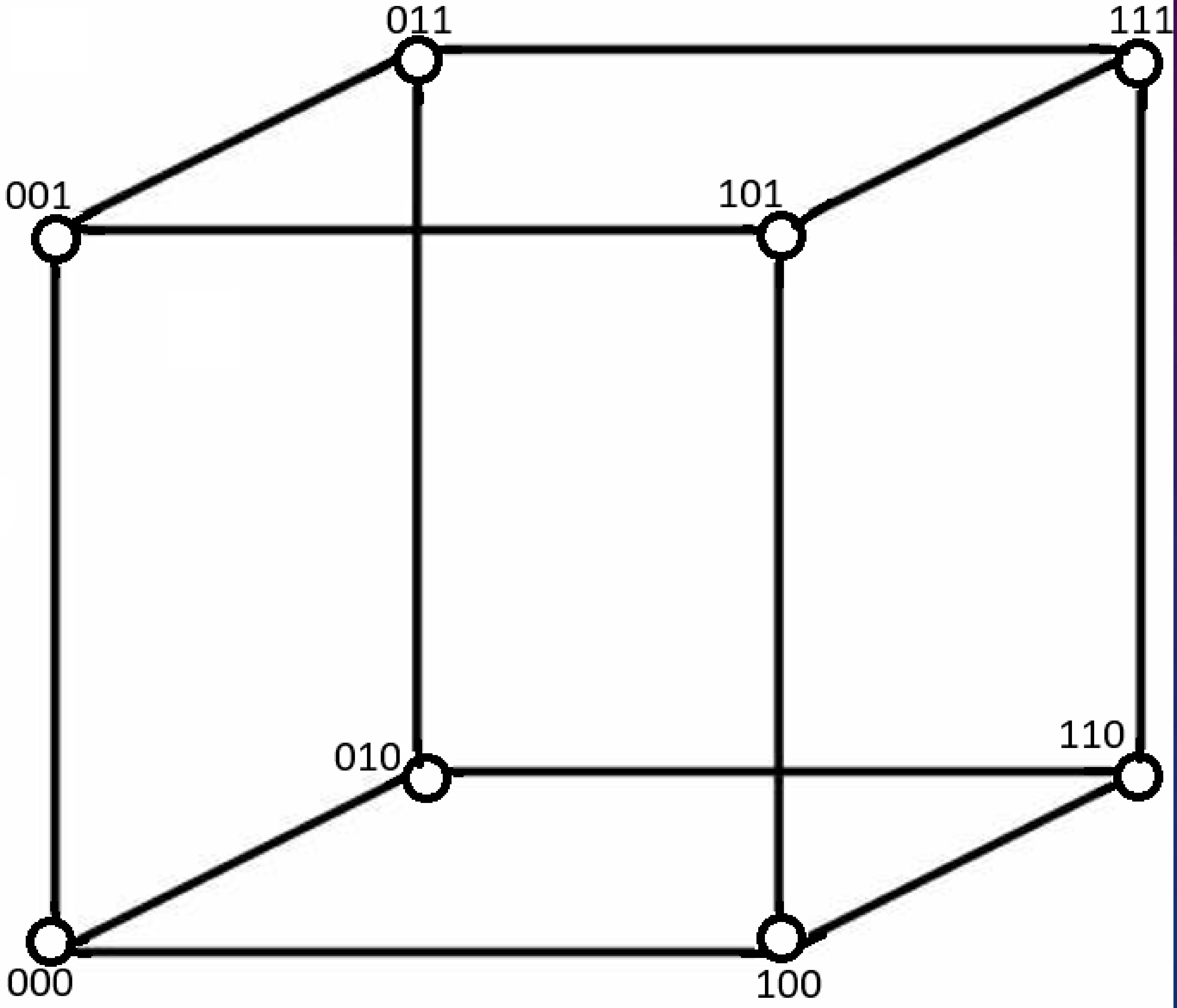
HAMMING CUBE
8 POSITIONS

Visualize the addressing failure from our example, A2 (leading bit) stuck high.

000 fails to 100

001 fails to 101

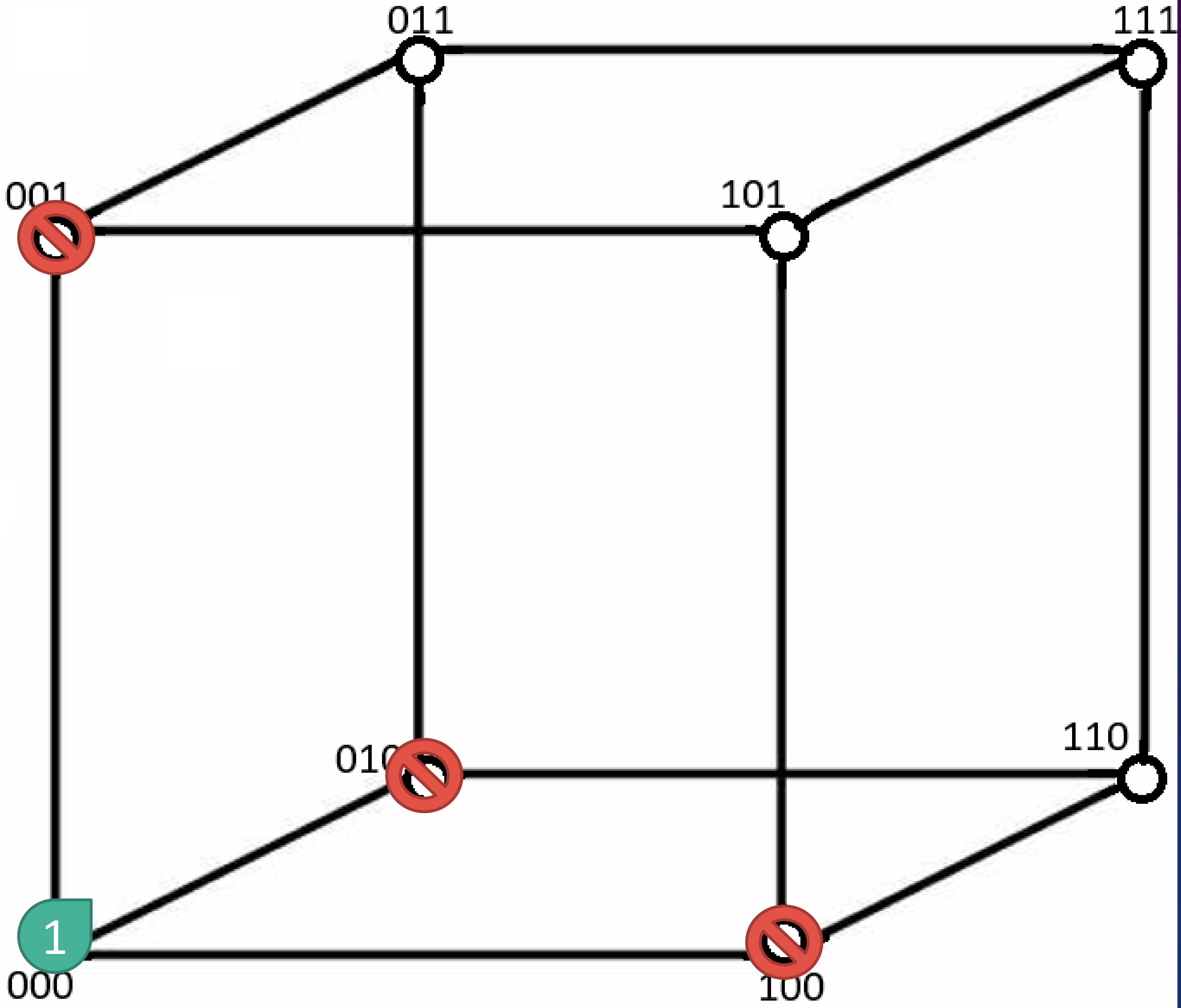
Etc…



HAMMING CUBE
8 POSITIONS

Any two vertices on this cube which are connected by an edge have a Hamming Distance of 1. (Hamming Adjacent)

In the event of an addressing failure, they would be susceptible 'fail-over' channels.

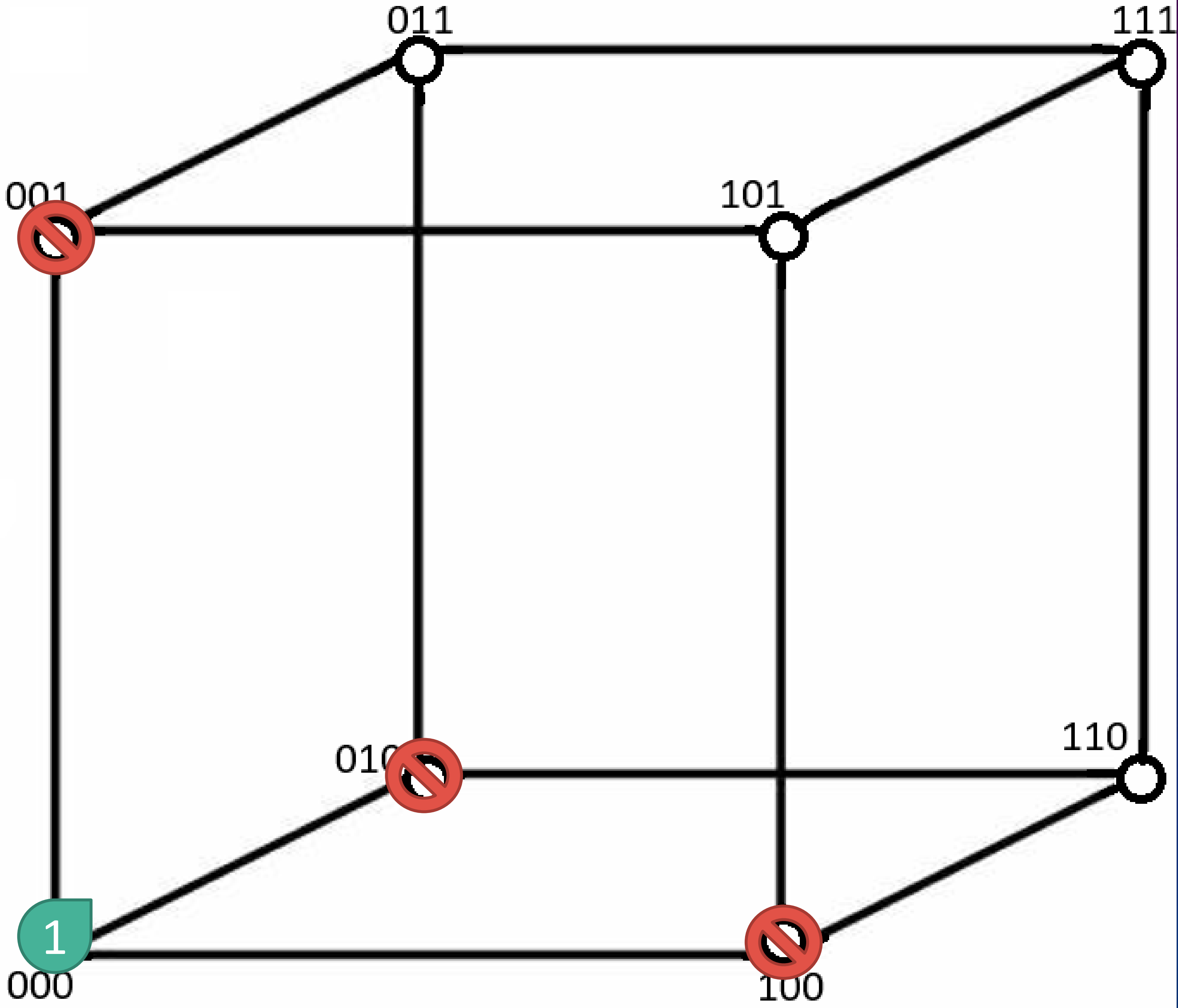


HAMMING CUBE
8 POSITIONS

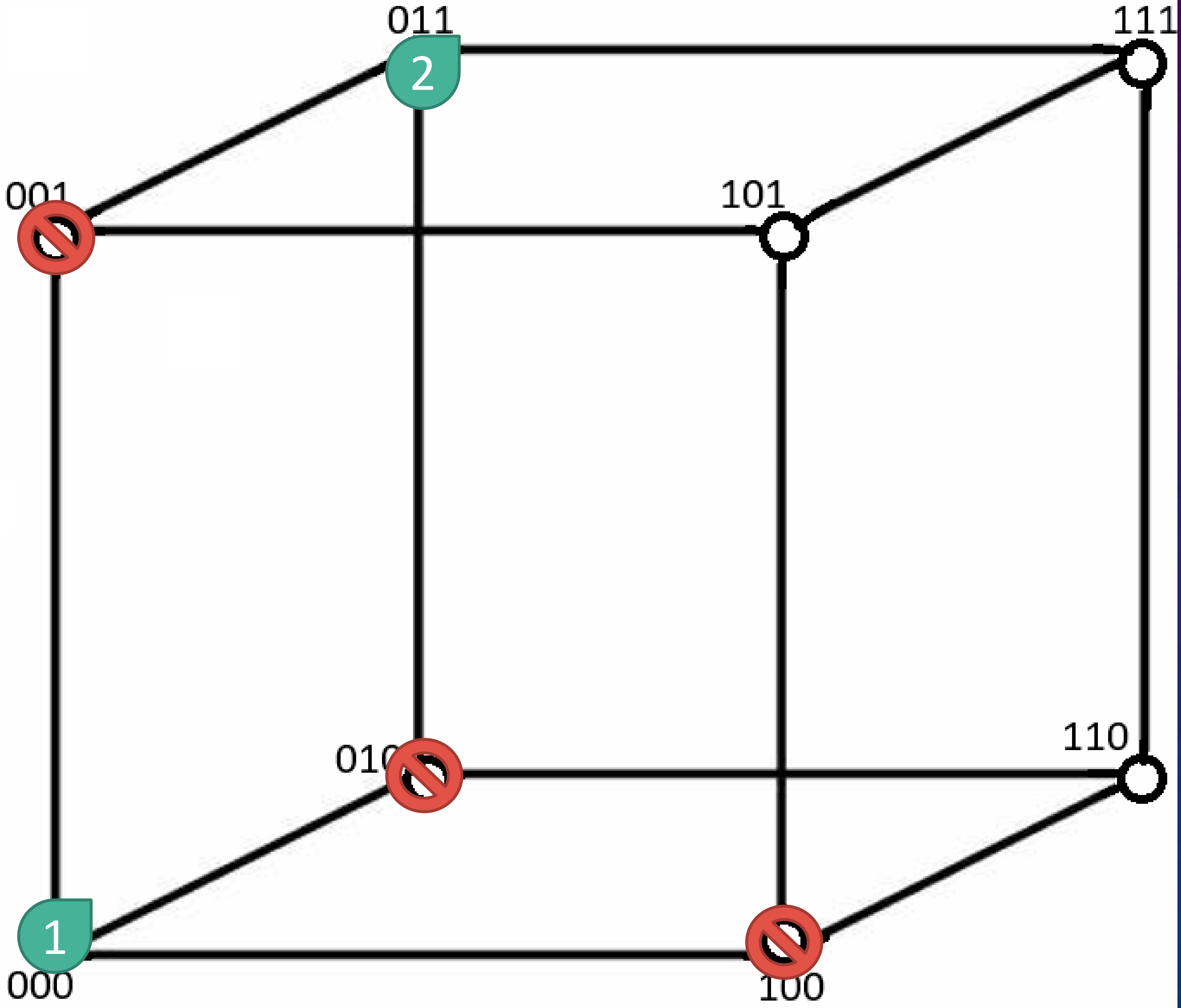
Let’s use this cube to place signals that cannot fail-over into another used channel.

If we begin by placing one of our signals in 000, that means 001, 010, and 100 should be kept un-assigned.

HAMMING CUBE
8 POSITIONS



So on, fill the next available channel and reserve each channel within a hamming distance of 1 as un-assigned



HAMMING CUBE

8 POSITIONS

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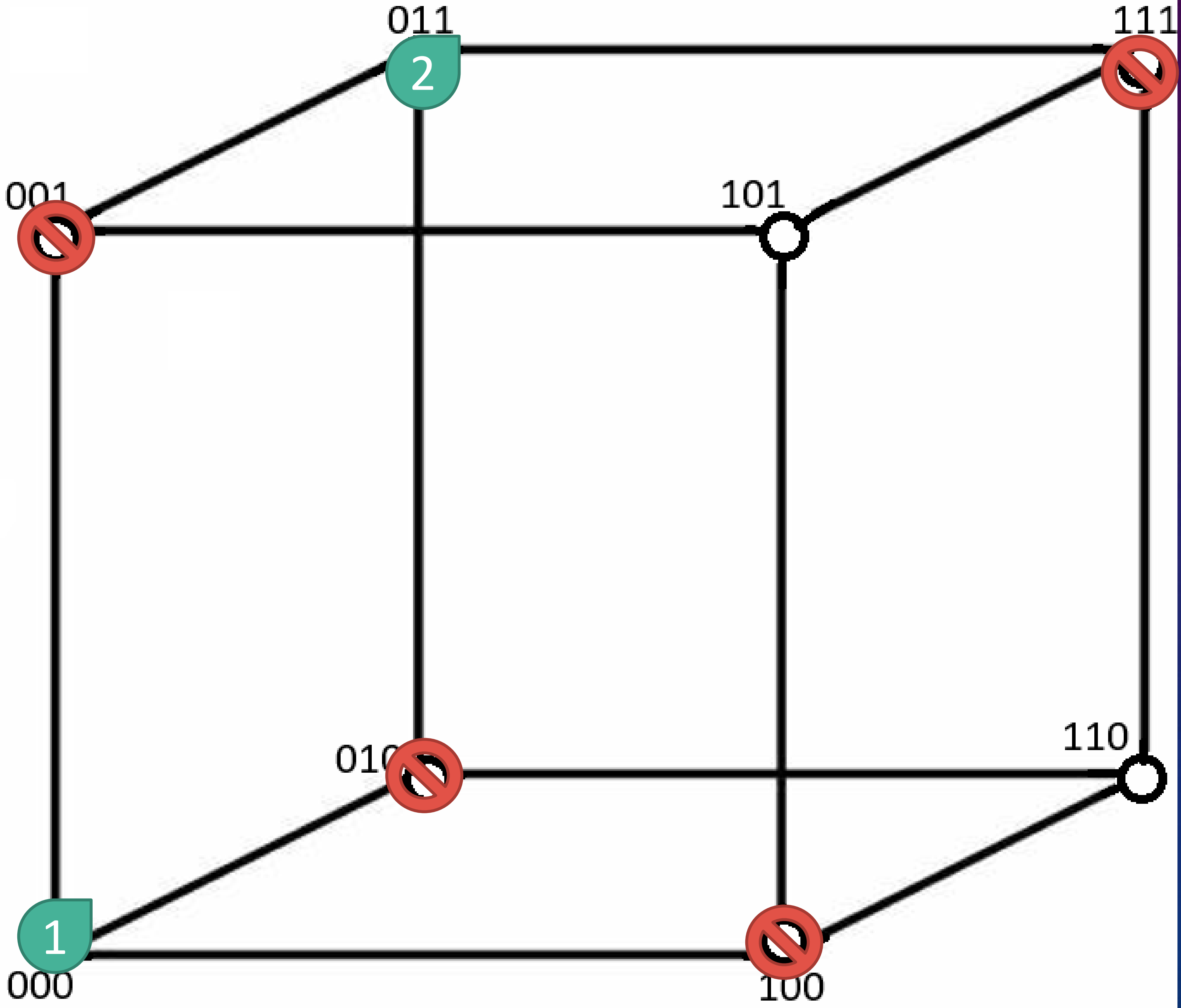

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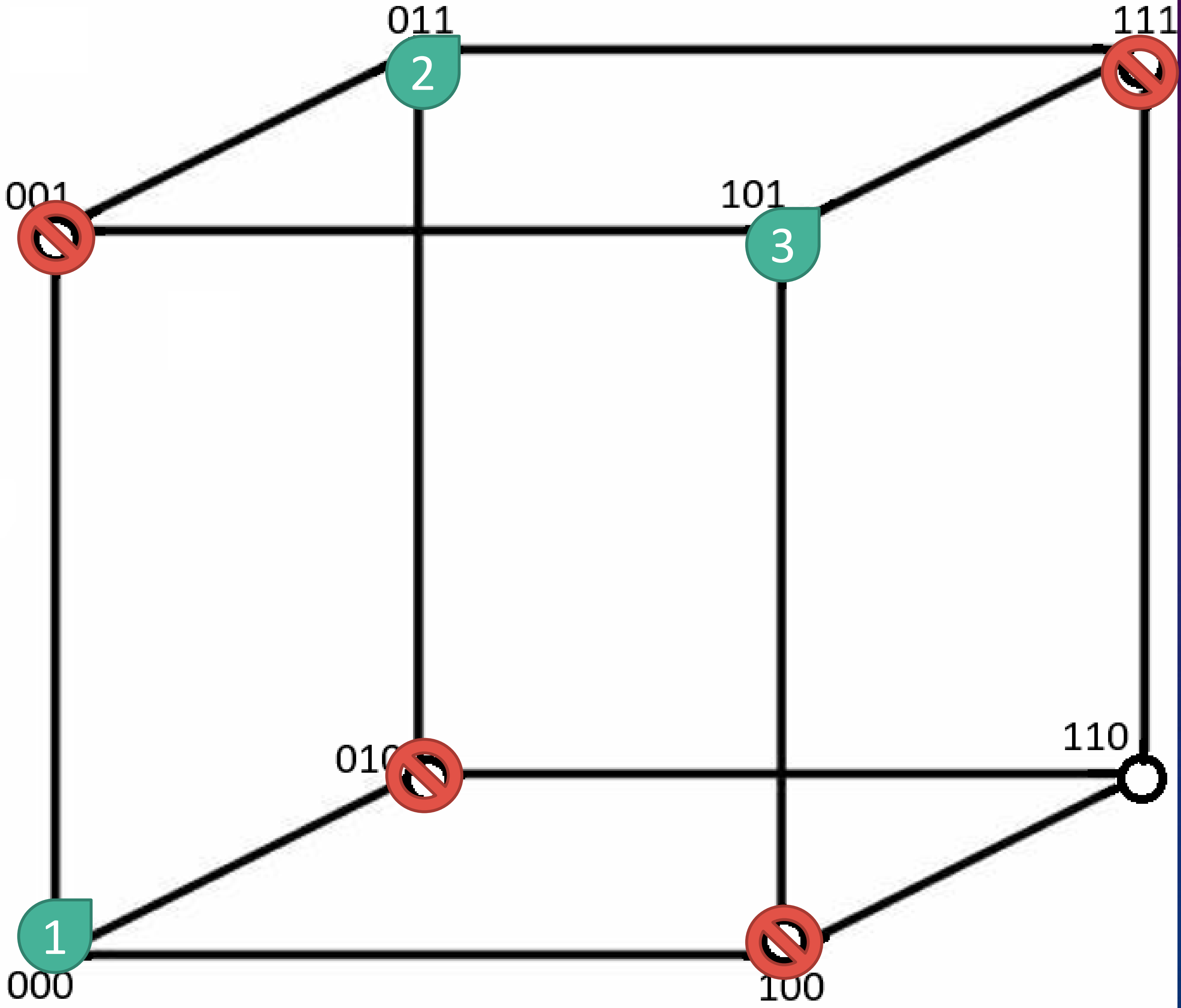

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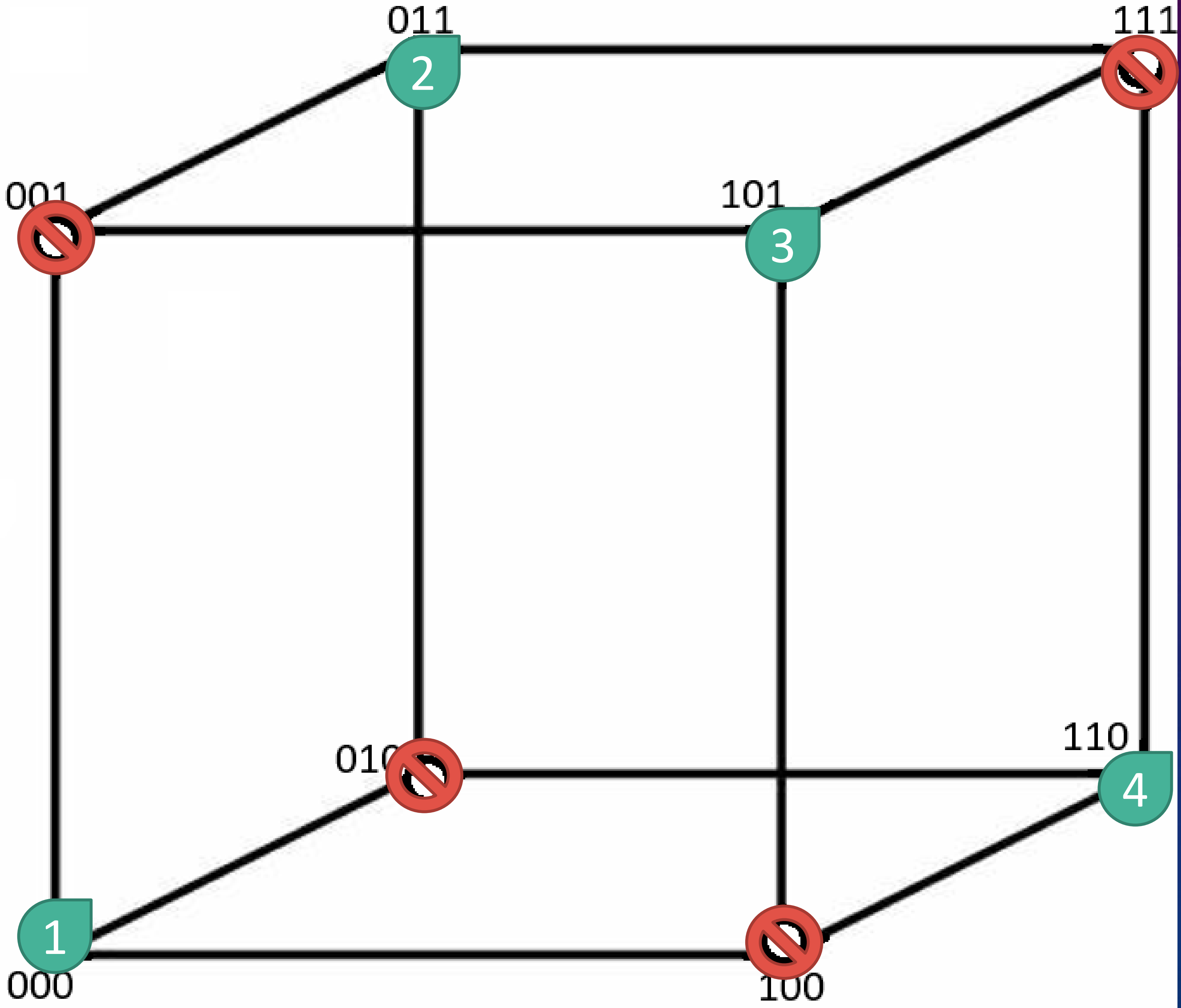

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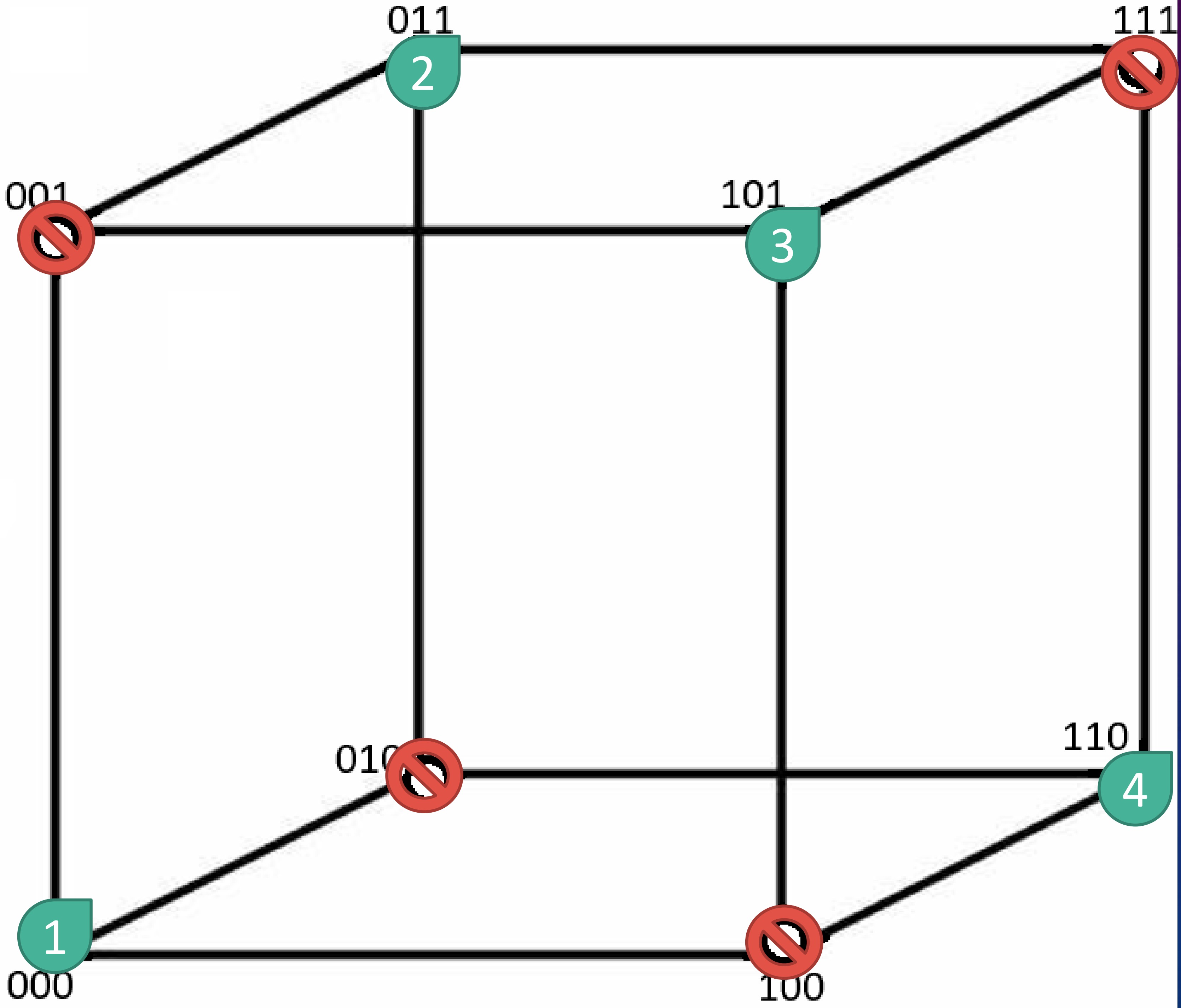


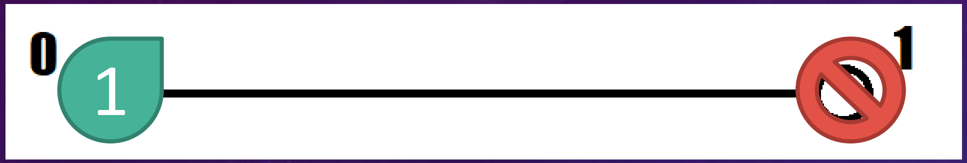
HAMMING CUBE

8 POSITIONS

An 8-to-1 MUX can accommodate 4 signals packed in this way.

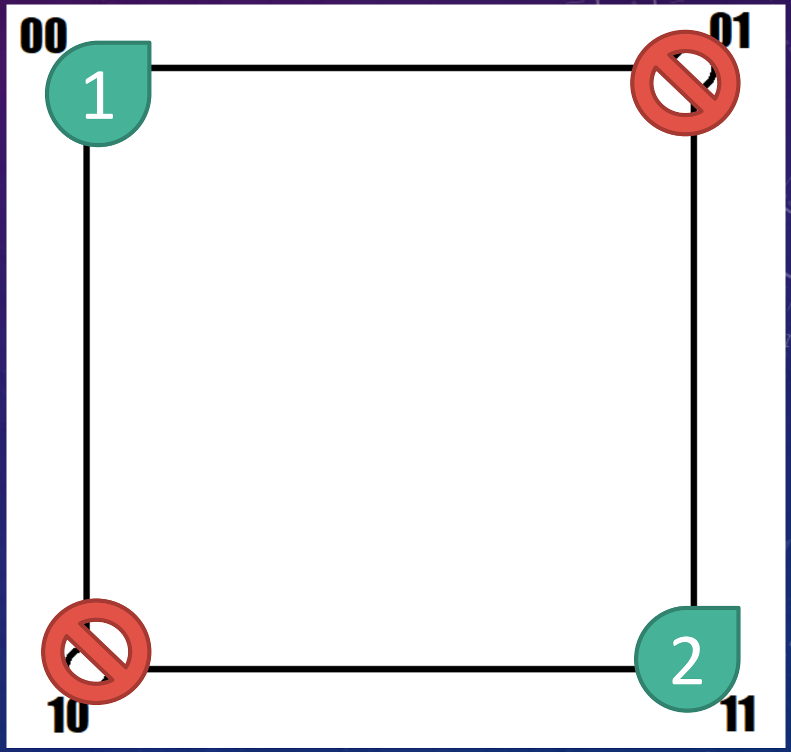
Multiplexers are commonly produced in 2-to-1, 4-to-1, 8-to-1, and 16-to-1

HAMMING LINE
2 POSITIONS

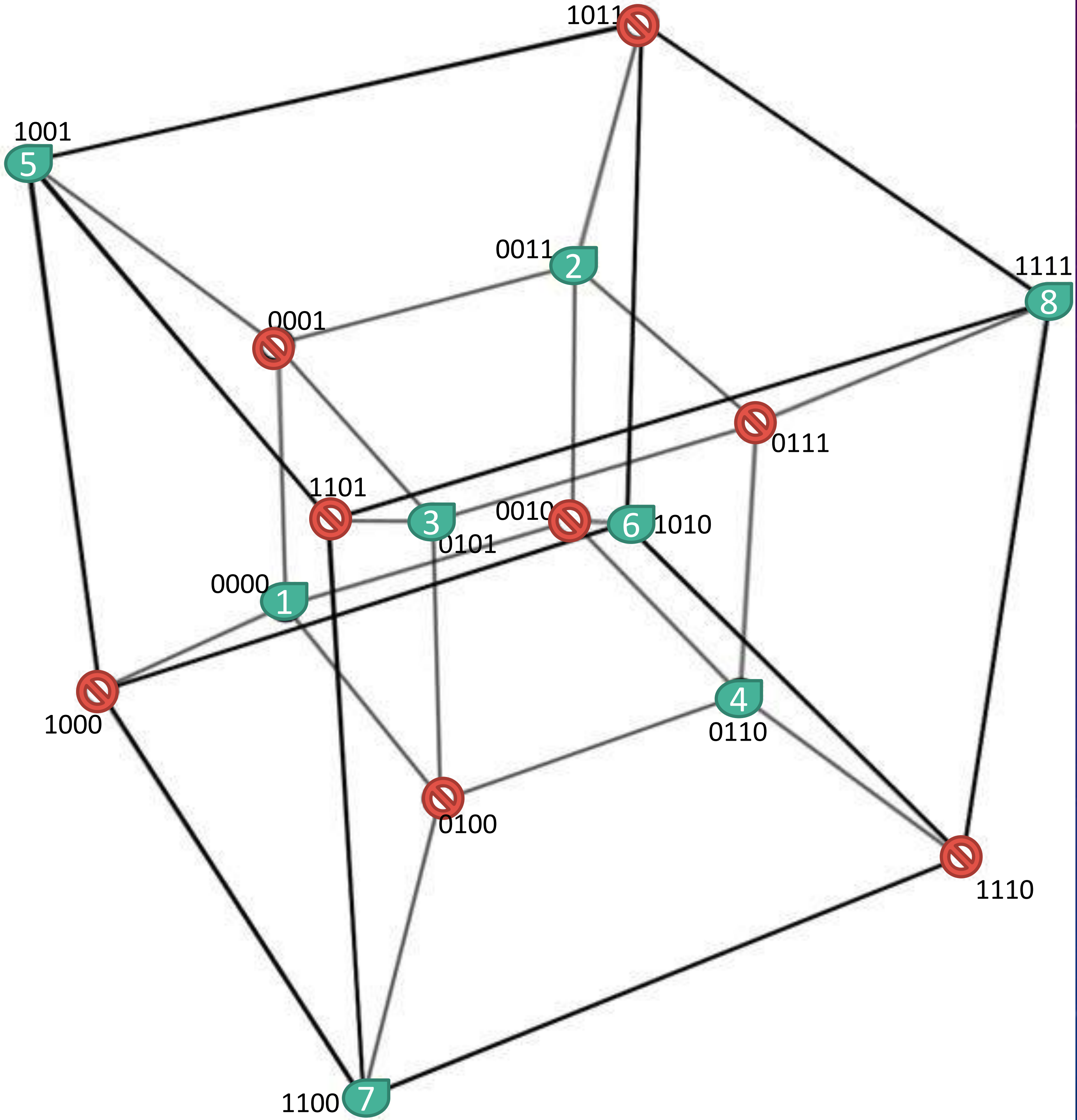


A 2-to-1 MUX (switch) can accommodate 1 signal packed in this way.

HAMMING SQUARE
4 POSITIONS



A 4-to-1 MUX can accommodate 2 signals packed in this way.



THE TESSERACT
16 POSITIONS

A 16-to-1 MUX can accommodate 8 signals packed in this way.

BEYOND THE LIMITS OF THE FEEBLE HUMAN MIND

N POSITIONS

N -> ∞

A 2^n-to-1 MUX can accommodate 2^{n-1} signals packed in this way.

OPTIMAL CHANNELIZATION

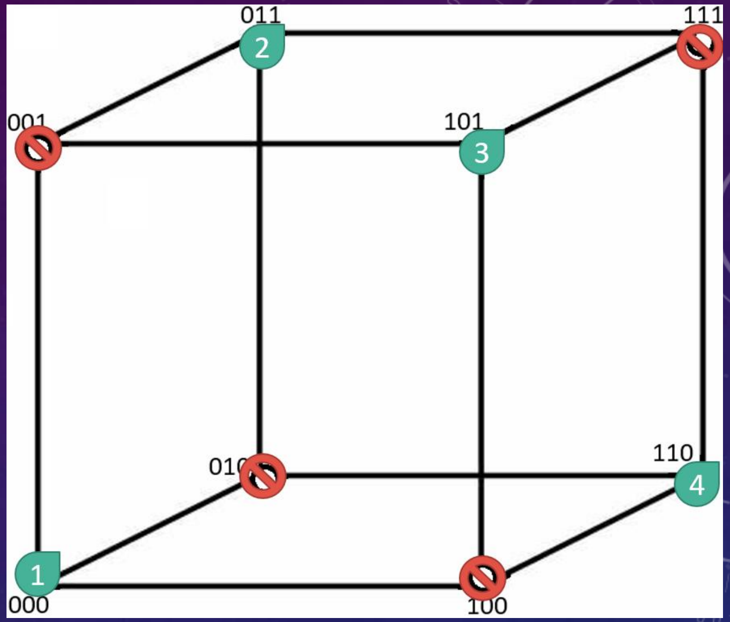
Apply this principle to our example:

Based on the Hamming Cube, An 8-to-1 MUX can accommodate 4 signals if each one is to have empty failover channels.

Our MUX has 5 signals to assign. What now?

1). Use a bigger MUX (16 to 1)

2). Identify another detection method



8 to 1 MUX				
Channel	A2	A1	A0	Sensor
0	0	0	0	Pressure Sensor 1
1	0	0	1	Pressure Sensor 2
2	0	1	0	5V Voltage Reference
3	0	1	1	Temp. Sensor 1
4	1	0	0	Temp. Sensor 2
5	1	0	1	N/A
6	1	1	0	N/A
7	1	1	1	N/A

OPTIMAL CHANNELIZATION

1). Use a bigger MUX (16 to 1)

Depending on your project, this can be a viable solution. Multiplexers are high-reliability parts and a larger MUX adds almost no cost, weight, or complexity.

16 to 1 MUX					
Channel	A3	A2	A1	A0	Sensor
0	0	0	0	0	Pressure Sensor 1
1	0	0	0	1	N/A
2	0	0	1	0	N/A
3	0	0	1	1	Pressure Sensor 2
4	0	1	0	0	N/A
5	0	1	0	1	5V Voltage Reference
6	0	1	1	0	Temp. Sensor 1
7	0	1	1	1	N/A
8	1	0	0	0	N/A
9	1	0	0	1	Temp. Sensor 2
10	1	0	1	0	N/A
11	1	0	1	1	N/A
12	1	1	0	0	N/A
13	1	1	0	1	N/A
14	1	1	1	0	N/A
15	1	1	1	1	N/A

OPTIMAL CHANNELIZATION

2). Identify another detection method

One of these signals is a 5V reference voltage, so we know its expected value. Let's say the nominal range of the pressure and temperature sensors are 10-15 volts – if this is the case, an erroneously telemetered 5V could still be detected as out-of-family, in the same manner as the constant 0V of the unassigned channel.

8 to 1 MUX				
Channel	A2	A1	A0	Sensor
0	0	0	0	Pressure Sensor 1
1	0	0	1	5V Voltage Reference
2	0	1	0	N/A
3	0	1	1	Pressure Sensor 2
4	1	0	0	N/A
5	1	0	1	Temp. Sensor 1
6	1	1	0	Temp. Sensor 2
7	1	1	1	N/A

NOTE ON DETECTION METHODS

In our example, the pressure and temperature sensors share a nominal voltage range, 10-15V. 10V on the pressure channel may mean 20 PSI, while 10V on the temp channel is 70C.

If your signals have sufficiently different expected ranges, you may be able to assign them in Hamming-adjacent channels and still achieve detection.

In this way you achieve high information density and still detect all addressing failures

8 to 1 MUX				
Channel	A2	A1	A0	Sensor
0	0	0	0	Pressure Sensor 1
1	0	0	1	Liquid Level Sensor 1
2	0	1	0	Liquid Level Sensor 2
3	0	1	1	Pressure Sensor 2
4	1	0	0	Liquid Level Sensor 3
5	1	0	1	Pressure Sensor 3
6	1	1	0	Pressure Sensor 4
7	1	1	1	Liquid Level Sensor 4

SUMMARY

- An addressing error causes the software to request, or the MUX to telemeter, a Hamming-Adjacent incorrect channel
- If the incorrect data is used in calculations, expect errors
- An un-assigned MUX channel will return a constant 0V
- Make sure addressing errors always cause your sensors to telemeter an out-of-range value, by placing un-assigned channels or sensors with incompatible ranges in Hamming-Adjacent channels
- Use software to detect out-of-range sensor outputs, and DQ from use

Contact: Gwyer Sinclair, GWYER.Q.SINCLAIR@NASA.GOV

BACKUP – SENSOR VOLTAGES

Sensors convert some physical phenomena into a voltage. Software reads this voltage and interprets it to generate the reading.

A certain pressure sensor experiencing 20 PSI produces 10V on its output line.

A certain temperature sensor experiencing 50 C produces 8V on its output line.

If the Temp Sensor's measurement is erroneously telemetered, software will think it is seeing 8V from a pressure sensor, and interpret that as 15 PSI. The software will underestimate the pressure.

BACKUP – GRAY CODE

What if my product addresses using Gray Code?

Gray Code is an ordering of Binary expressions such that each successive value is Hamming-Adjacent (differs by only one bit)

Often used in error correction, and to account for latecy of electromechanical switches

Gray Code changes the order, not the number of channels
The packing technique described here will still allow you to detect addressing errors

Decimal	Binary Expression				Gray Expression			
0	0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0	1
2	0	0	1	0	0	0	1	1
3	0	0	1	1	0	0	1	0
4	0	1	0	0	0	1	1	0
5	0	1	0	1	0	1	1	1
6	0	1	1	0	0	1	0	1
7	0	1	1	1	0	1	0	0
8	1	0	0	0	1	1	0	0
9	1	0	0	1	1	1	0	1
10	1	0	1	0	1	1	1	1
11	1	0	1	1	1	1	1	0
12	1	1	0	0	1	0	1	0
13	1	1	0	1	1	0	1	1
14	1	1	1	0	1	0	0	1
15	1	1	1	1	1	0	0	0

BACKUP – MULTIPLEXER TREES

What if my product needs to select from more than 16 signals on a single data line?

Larger MUX can be created from combinations of smaller MUX. This channelization technique will still be effective at allowing detection of addressing errors, though more complex with added hw.

BACKUP – MULTIPLEXER TREES

The channelization for a 32-to-1 MUX is shown at right. There are 16 channels with no hamming adjacency.

channel	A4	A3	A2	A1	A0	
0	0	0	0	0	0	X
1	0	0	0	0	1	
2	0	0	0	1	0	
3	0	0	0	1	1	X
4	0	0	1	0	0	
5	0	0	1	0	1	X
6	0	0	1	1	0	X
7	0	0	1	1	1	
8	0	1	0	0	0	
9	0	1	0	0	1	X
10	0	1	0	1	0	X
11	0	1	0	1	1	
12	0	1	1	0	0	X
13	0	1	1	0	1	
14	0	1	1	1	0	
15	0	1	1	1	1	X
16	1	0	0	0	0	
17	1	0	0	0	1	X
18	1	0	0	1	0	X
19	1	0	0	1	1	
20	1	0	1	0	0	X
21	1	0	1	0	1	
22	1	0	1	1	0	
23	1	0	1	1	1	X
24	1	1	0	0	0	X
25	1	1	0	0	1	
26	1	1	0	1	0	
27	1	1	0	1	1	X
28	1	1	1	0	0	
29	1	1	1	0	1	X
30	1	1	1	1	0	X
31	1	1	1	1	1	