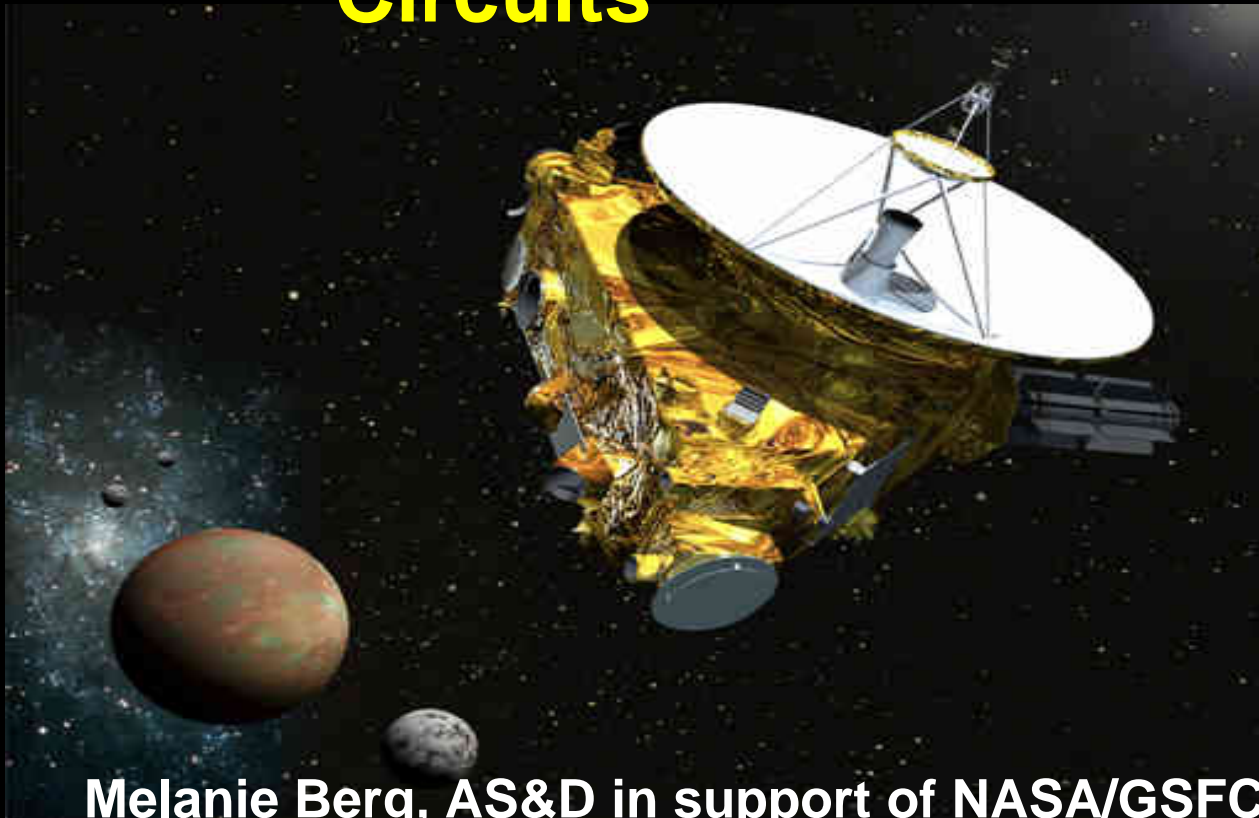


# Revisions to Conventional Clock Domain Crossing Methodologies in Triple Modular Redundant Circuits



**Melanie Berg, AS&D in support of NASA/GSFC**

**Melanie.D.Berg@NASA.gov**

**Kenneth LaBel, NASA/GSFC**





# Acronyms

- Application specific integrated circuit (ASIC)
- Block random access memory (BRAM)
- Block Triple Modular Redundancy (BTMR)
- Clock (CLK or CLKB)
- Clock to output time ( $t_{co}$ )
- Collected charge ( $Q_{coll}$ )
- Combinatorial logic (CL)
- Computer aided design (CAD)
- Configurable Logic Block (CLB)
- Configuration cross section ( $P_{configuration}$ )
- Critical charge ( $Q_{crit}$ )
- Digital Signal Processing Block (DSP)
- Distributed triple modular redundancy (DTMR)
- Dual interlocked cell (DICE)
- Dual redundancy (DR)
- Edge-triggered flip-flops (DFFs)
- Energy (E)
- Equivalence Checking (EC)
- Error detection and correction (EDAC)
- Field programmable gate array (FPGA)
- Finite state machine (FSM)
- Flip flop (DFF)
- Frequency of capture domain B ( $f_{clkB}$ )
- Frequency of incoming data ( $f_{DataA}$ )
- Functional logic cross section ( $P_{functionalLogic}$ )
- Gate Level Netlist (EDF, EDIF, GLN)
- Hardware Description Language (HDL)
- Hold time ( $t_h$ )
- Input – output (I/O)
- Linear energy transfer (LET)
- Local triple modular redundancy (LTMR)
- Mean Time between failure (MTBF)
- NASA Electronic Parts and Packaging (NEPP)
- Negative doped with electrons ( $N^+$ )
- Operational frequency ( $f_s$ )
- Power on reset (POR)
- Place and Route (PR)
- Positive doped with holes ( $P^+$ )
- Radiation Effects and Analysis Group (REAG)
- Set up time ( $t_{su}$ )
- Single event functional interrupt (SEFI)
- Single event functional interrupt cross section ( $P_{SEFI}$ )
- Single event effects (SEEs)
- Single event latch-up (SEL)
- Single event transient (SET)
- Single event upset (SEU)
- Single event upset cross-section ( $\sigma_{SEU}$ )
- System cross section ( $P(f_s)_{error}$ )
- Time delay ( $\tau_{dly}$ )
- Voltage connected to positive rail ( $V_{DD}$ )
- Voltage connected to ground rail ( $V_{SS}$ )

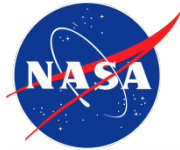


# Agenda

- **Metastability**
- **Single Event Upsets (SEUs).**
- **Triple modular redundancy (TMR).**
- **Metastability filters and TMR.**







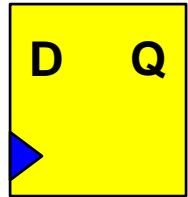
# Metastability

- **Cause:** Introducing an asynchronous signal into a synchronous (edge triggered) system... Or creating a combinatorial logic path that does not meet timing constraints.
- **Effect:**
  - Flip-flop (DFF) clock captures signal during window of vulnerability.
  - DFF output Hovers at a voltage level between high and low, causing the output transition to be delayed beyond the specified clock to output ( $t_{CO}$ ) delay.
- Probability that the DFF enters a metastable state and the time required to return to a stable state varies on the process technology and on ambient conditions.
- Generally the DFF quickly returns to a stable state.  
**However, the resultant stable state is not deterministic**

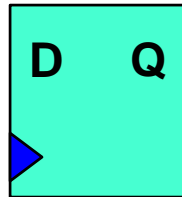


# Metastability Timing Diagram (Destination DFF)

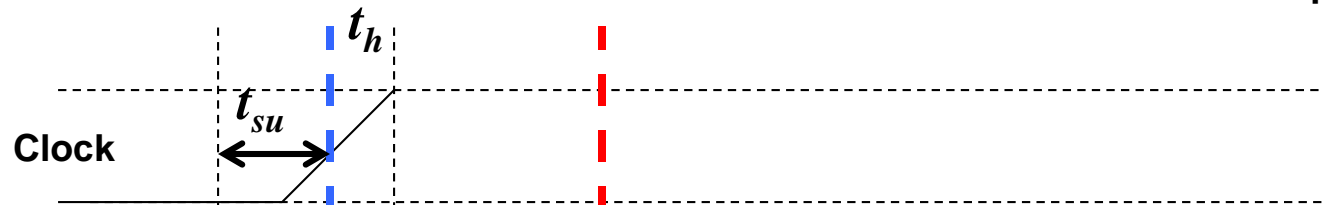
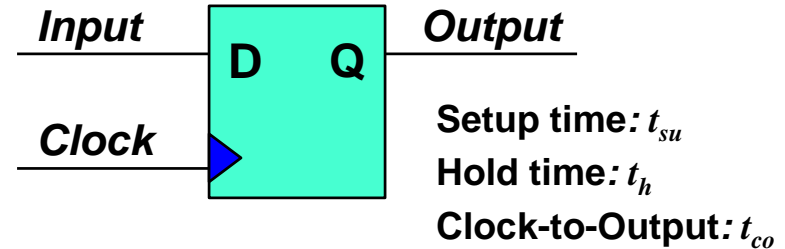
Source DFF  
Clock A



Destination DFF  
Clock B



*Destination DFF*

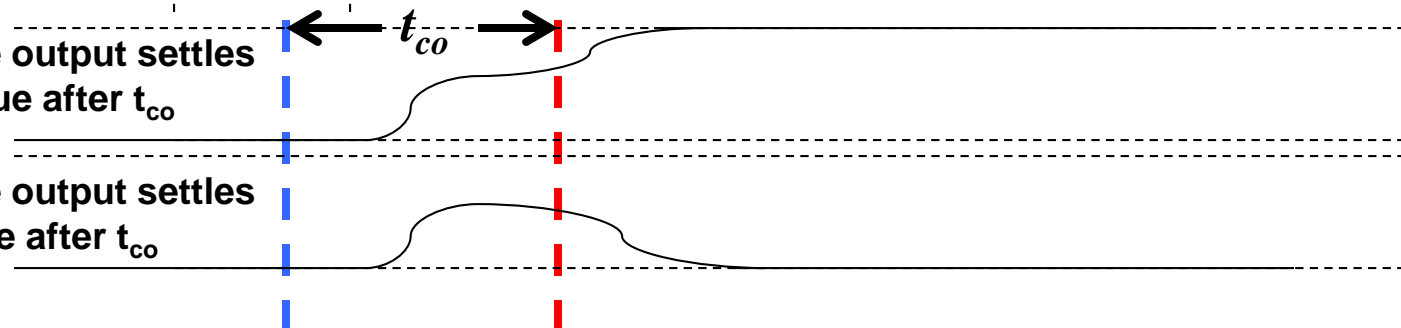


**Cause:** Input violates  $t_{su}$

**Effects:**

Metastable output settles  
to new value after  $t_{co}$

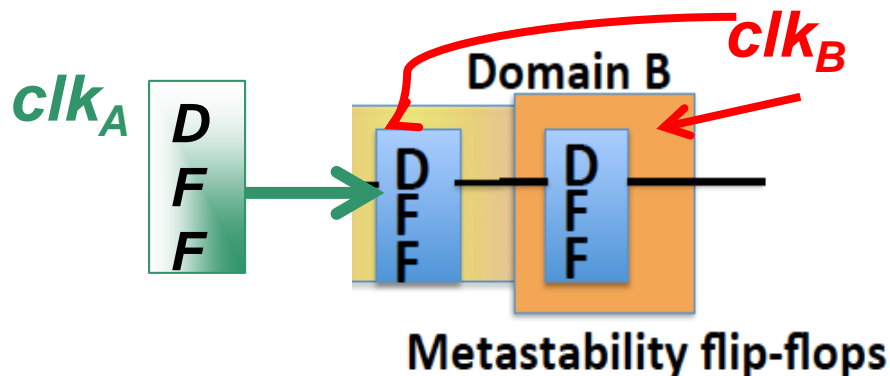
Metastable output settles  
to old value after  $t_{co}$





# Solution: Metastability Filter

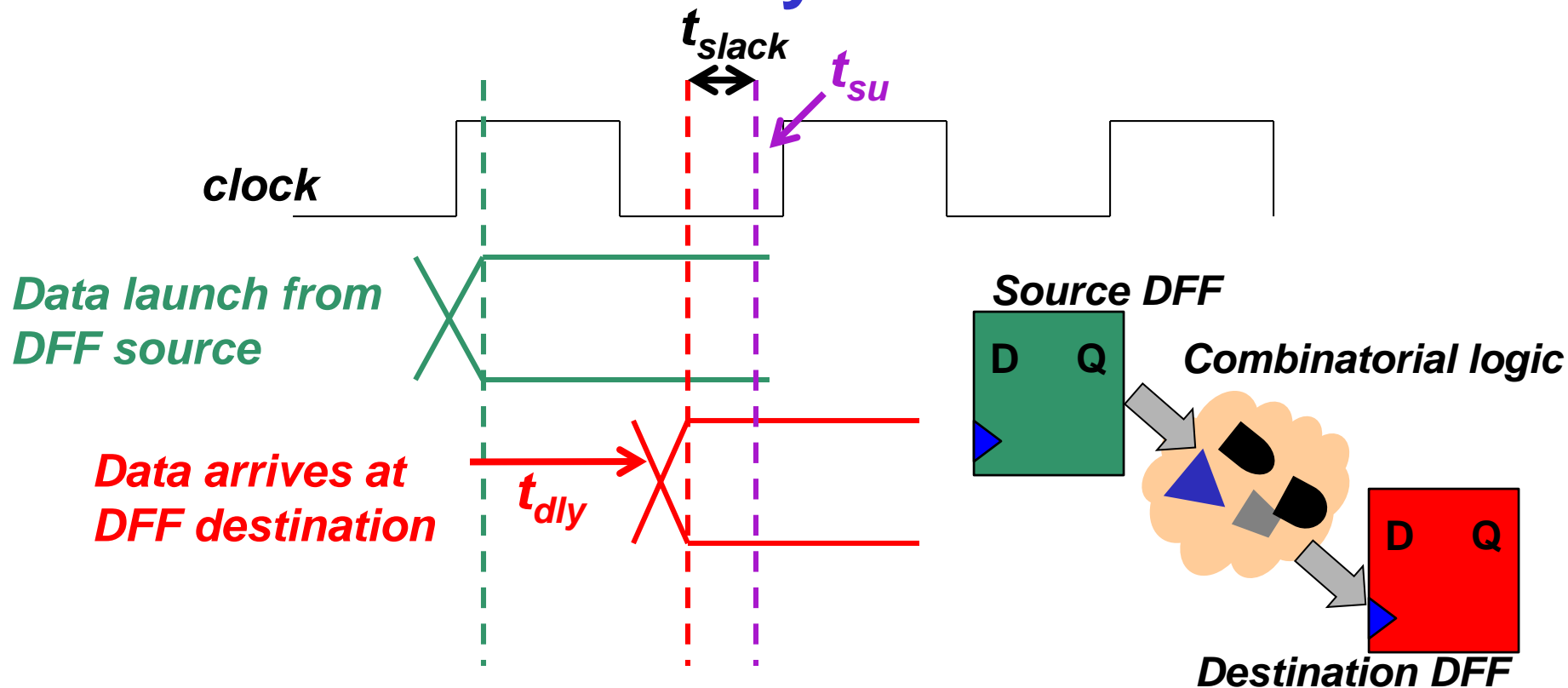
- Incoming signal is clocked in Domain A.
- Destination signals are clocked in Domain B.
- Filter: Use a capture DFF and at least one protection DFF.
  - Both DFFs are clocked in the capture domain.
  - The first DFF is expected to go metastable.
  - The second DFF is used to protect the rest of the system from potential metastable output.
  - However, there is no guarantee that the second DFF will not also become metastable. Metastability filters have a mean time between failure (MTBF).
  - Depends on slack time ( $t_{slack}$ ) between the metastability DFFs; process parameters ( $c1$  and  $c2$ ); frequency of incoming data ( $f_{DataA}$ ); and frequency of capture domain ( $f_{clkB}$ ).



$$MTBF = \frac{e^{t_{slack}/c2}}{c1 \times f_{DataA} \times f_{clkB}}$$



# Slack Time ( $t_{\text{slack}}$ ) between Metastability DFFs



- Nets and combinatorial logic add delay.
- Delay reduces slack time.
- Metastability filter rule: no combinatorial logic between metastability filter DFFs; and connection net length must be minimized.

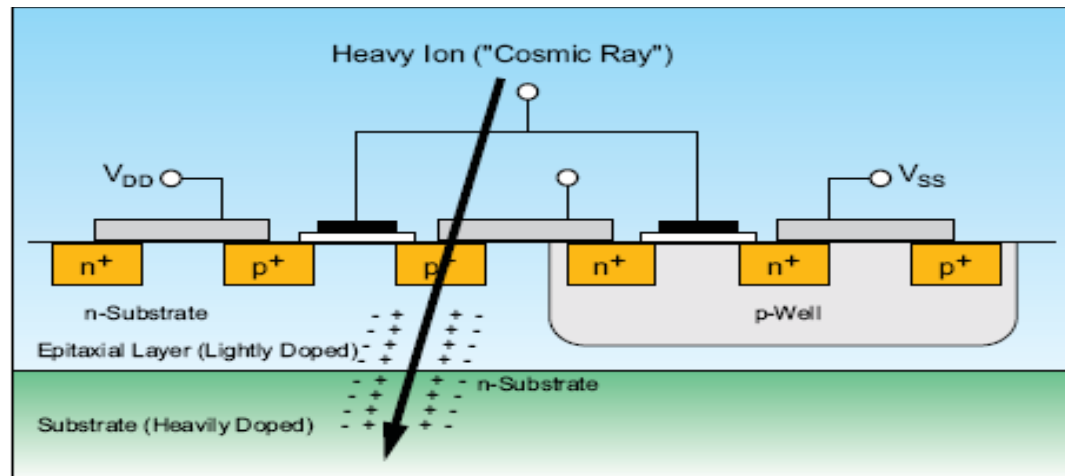
$$MTBF = \frac{e^{t_{\text{slack}/c2}}}{c1 \times f_{\text{DataA}} \times f_{\text{clkB}}}$$



# Device Penetration of Heavy Ions and Linear Energy Transfer (LET)



- LET characterizes the deposition of charged particles.
- Based on average energy (E) loss per unit path length (x) (stopping power).
- Mass is used to normalize LET to the target material.

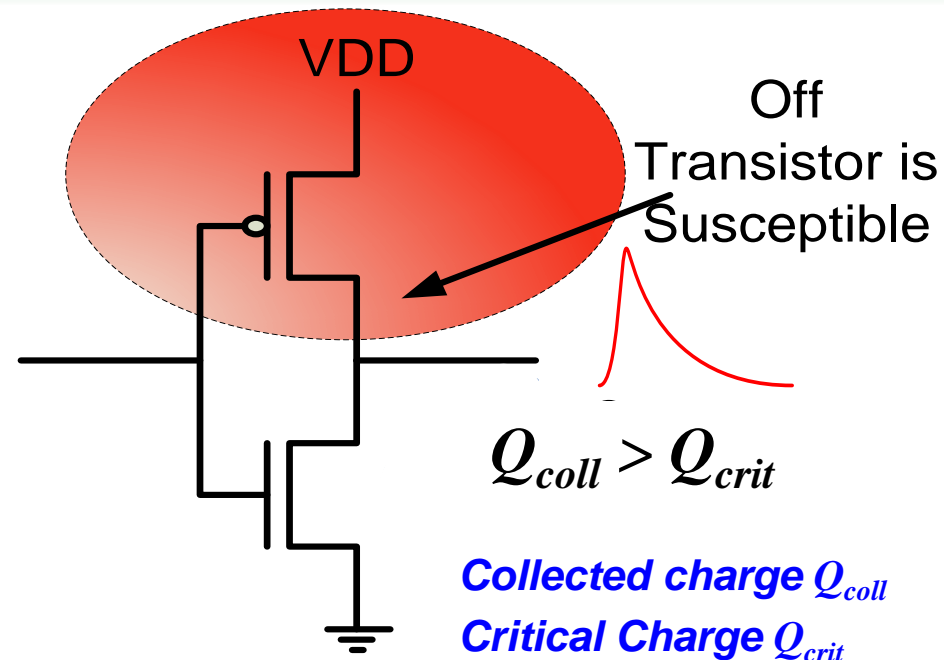


$$LET = \frac{1}{\rho} \frac{dE}{dx} ; MeV \frac{cm^2}{mg}$$

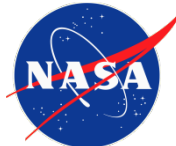
*Density of target material*      *Units*

**Single event transient (SET)**

**Single event upset (SEU)**







# How SEUs Affect FPGAs

- SEU and SET error signatures vary between FPGA devices:
  - Temporary glitch (transient)
  - Change of state (in correct state machine transitions)
  - Global upsets: Loss of clock or unexpected reset
  - Route breakage (no signal can get through)
  - Configuration corruption
  - Current jumps or increases (contention)

$$P(fs)_{error} \propto P_{Configuration} + P(fs)_{functionalLogic} + P_{SEFI}$$

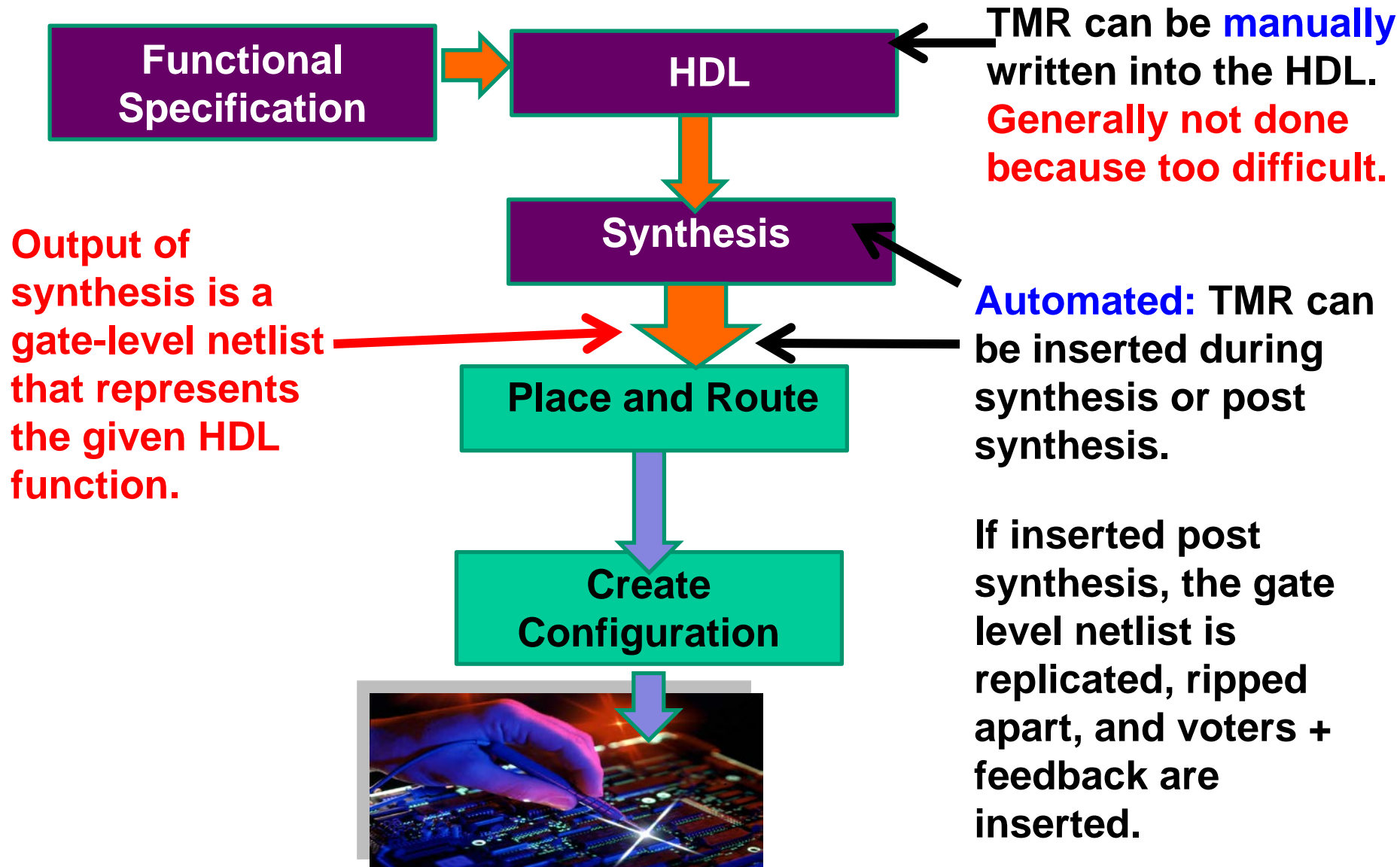
<i>System malfunction</i>	<i>Configuration SEU that causes malfunction</i>	<i>Sequential and Combinatorial logic (CL) events in data path</i>	<i>Glitches in global Routes and Hidden Logic</i>
-------------------------------	--	--	---

***Triple modular redundancy (TMR):  
A common approach to SEU mitigation.***





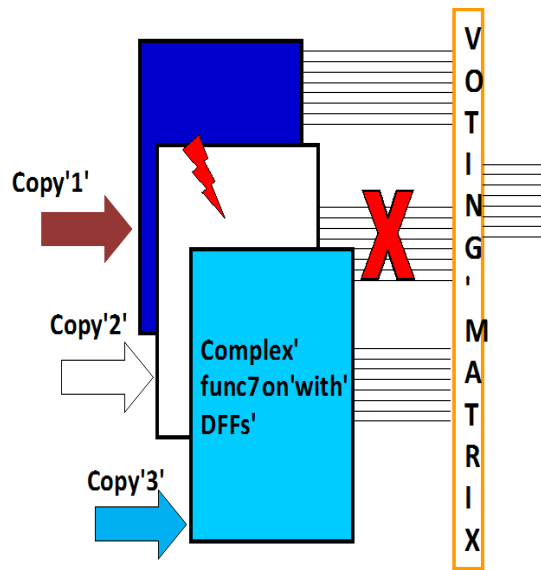
# How To Insert TMR into A Design:



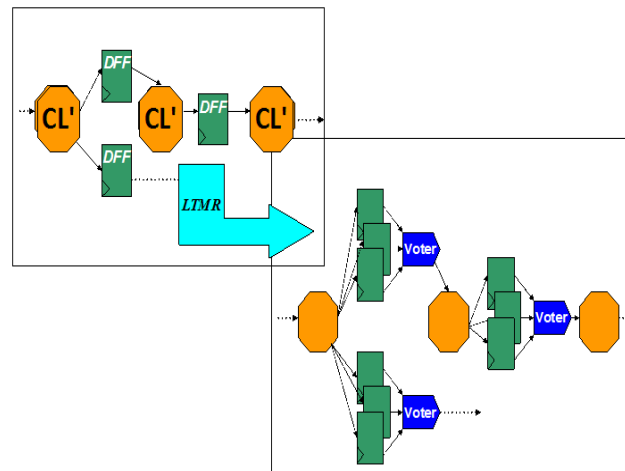
HDL: Hardware description language



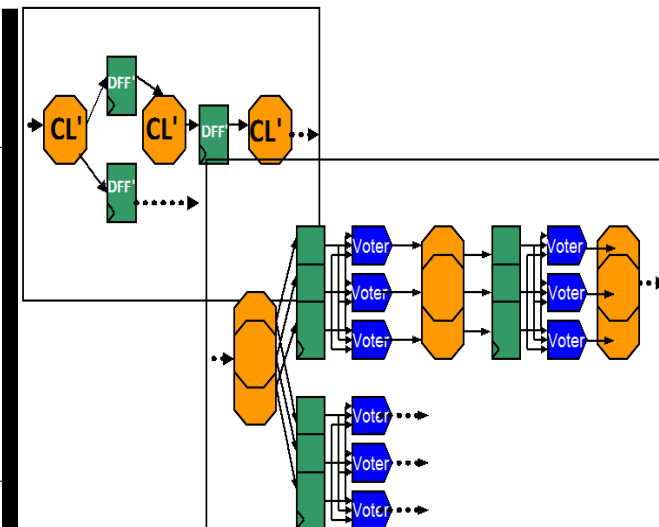
# Various TMR Schemes: Different Topologies



**Block diagram of block TMR (BTMR):** a complex function containing combinatorial logic (CL) and flip-flops (DFFs) is triplicated as three black boxes; majority voters are placed at the outputs of the triplet.



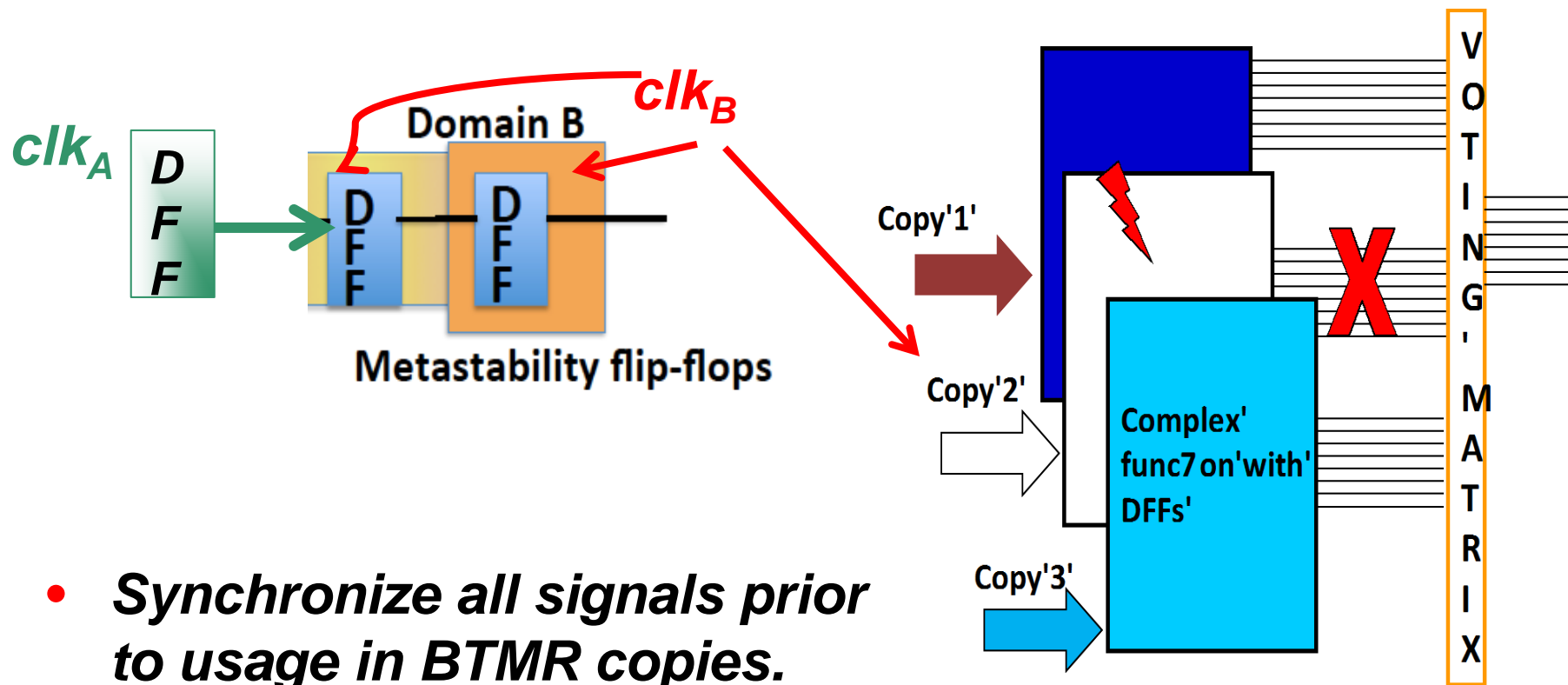
**Block diagram of local TMR (LTMR):** only flip-flops (DFFs) are triplicated and data-paths stay singular; voters are brought into the design and placed in front of the DFFs.



**Block Diagram of distributed TMR (DTMR):** the entire design is triplicated except for the global routes (e.g., clocks); voters are brought into the design and placed after the flip-flops (DFFs). DTMR masks and corrects most single event upsets (SEUs).



# BTMR And Metastability

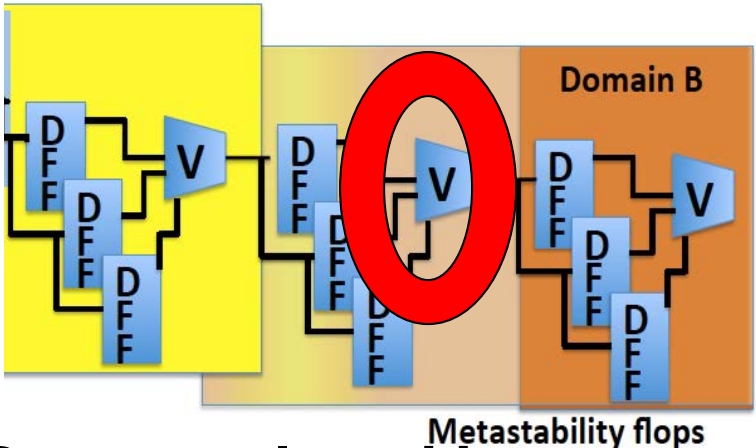
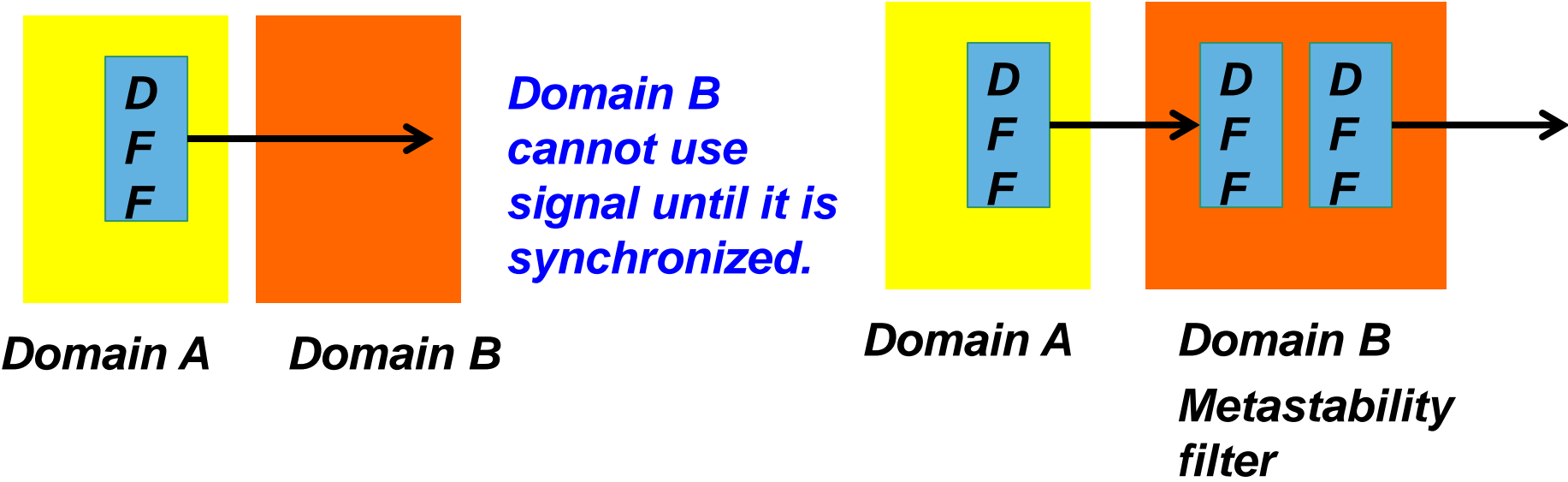


- ***Synchronize all signals prior to usage in BTMR copies.***
- ***This will require pulling out internal metastability filters contained in the each copy.***

***All three copies share  $clk_B$***



# LTMR And Metastability



**LTMR: voter placed between metastability filters. Violation**



# LTMR And Metastability

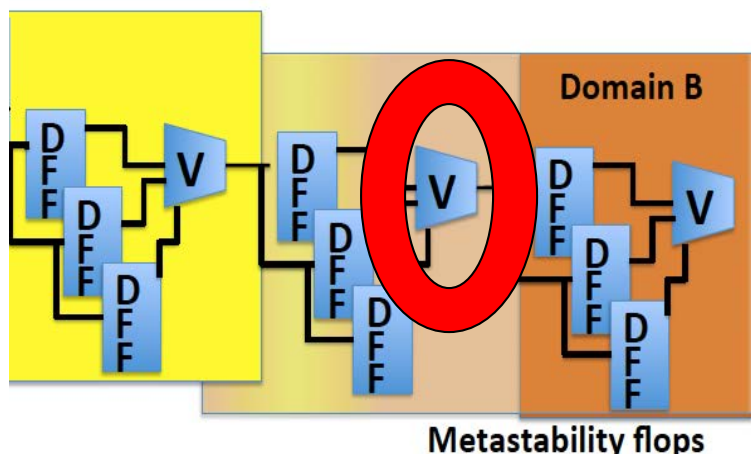
$$MTBF = \frac{e^{t_{slack/c2}}}{c1 \times f_{DataA} \times f_{clkB}}$$

Mean time between failure (MTBF)

C2 and C1 are process dependent constants.

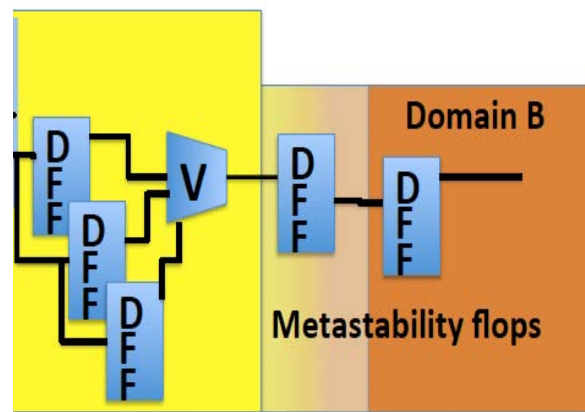
$f_{clkB}$  is the capture clock domain frequency.

$f_{DataA}$  is the maximum data switching frequency.



Voter placed between metastability filters.

**Violation**

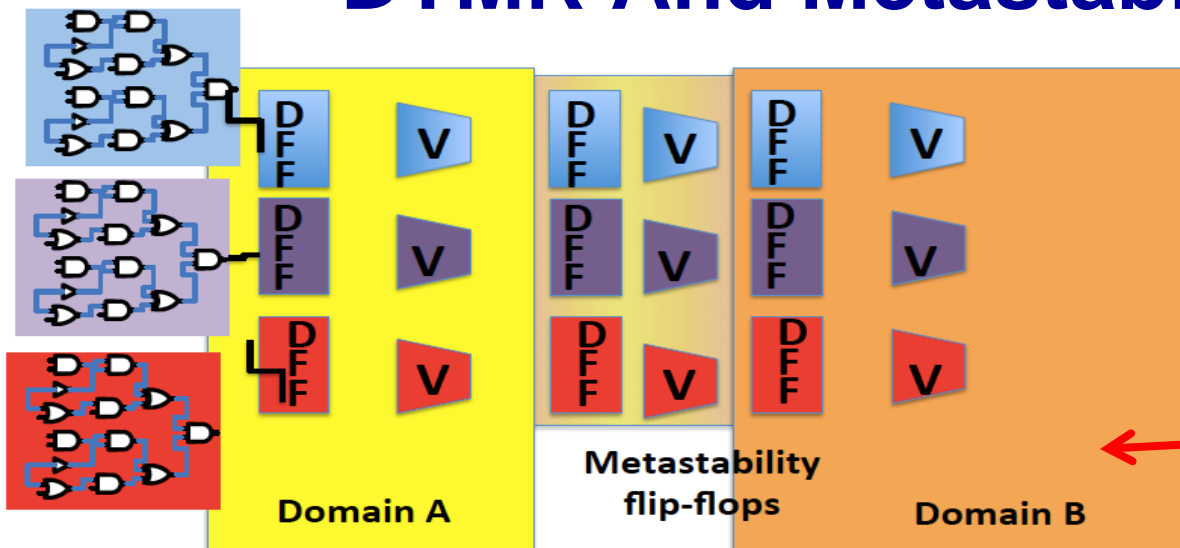


One solution is to remove the voters between metastability DFFs

Another solution is to include additional DFFs in the metastability filter (increase  $t_{slack}$ )



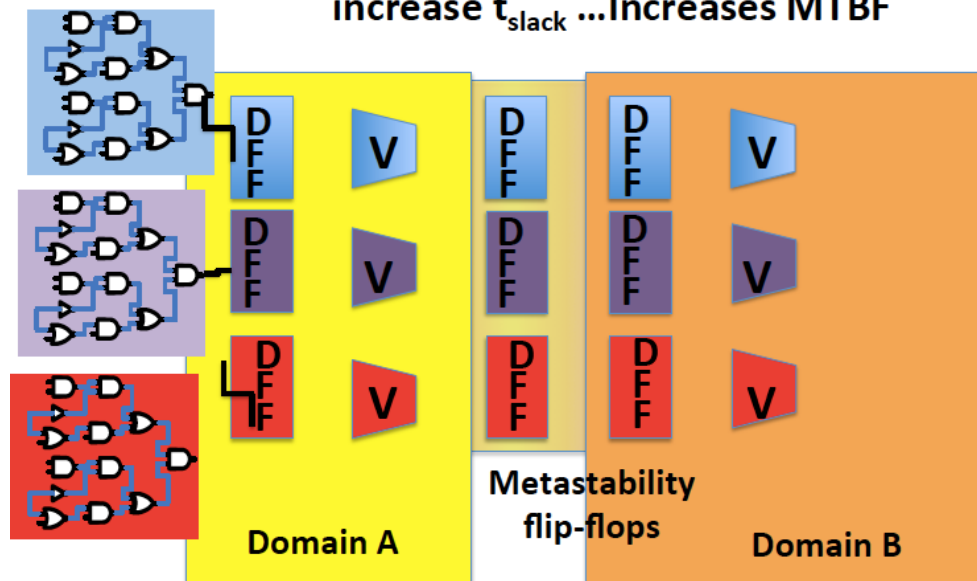
# DTMR And Metastability



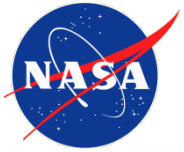
***Wrong implementation: voters are in the metastability filter***

Delete Voters and tightly place DFFs...  
increase  $t_{\text{slack}}$  ...Increases MTBF

Another solution is to include additional DFFs in the metastability filter (increase  $t_{\text{slack}}$ )







# Summary

- **Complex systems require multiple clock domains.**
- **In a synchronous design, metastability filters are required to reliably capture signals that source from separate clock domains.**
- **In order to reduce MTBF in metastability filters  $t_{\text{slack}}$  must be minimized: no combinatorial logic and short routes between metastability DFFs.**
- **Automated TMR tools have not been handling metastability filters correctly.**
- **We show the update to TMR automated tools for the following TMR methodologies:**
  - BTMR,      — LTMR,      — DTMR.