Air Traffic Control

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Thanks to D. Iamratanakul and J. Yoo for slides

U. Of Washington

Mostly it is rainy ---` good for the trees

Picture by Prof. Szu-Chi Tien

Speaking of adverse weather…

It is one of the main cause for delays -- topic of todays talk

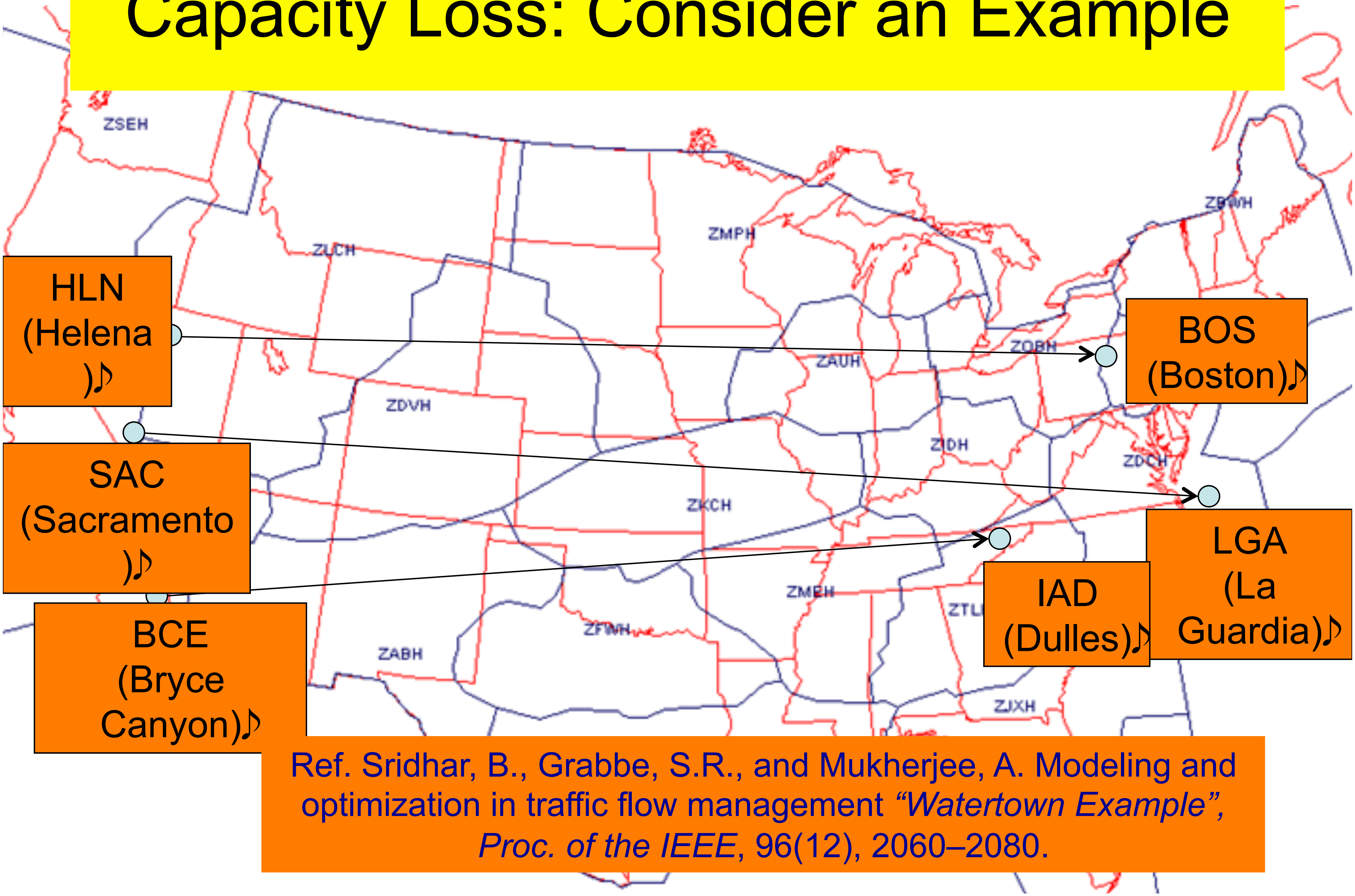
Outline of Talk

- Background: Adverse Weather Playbooks
- Problem: Route-capacity loss with merges
- Solution: Merge-free Playbooks
- Challenges in en-route CRP design
- Proposed approach to en-route CRP
- Guaranteed Conflict Free en-route CRP
- Conclusion

A Challenge in Air Traffic Control

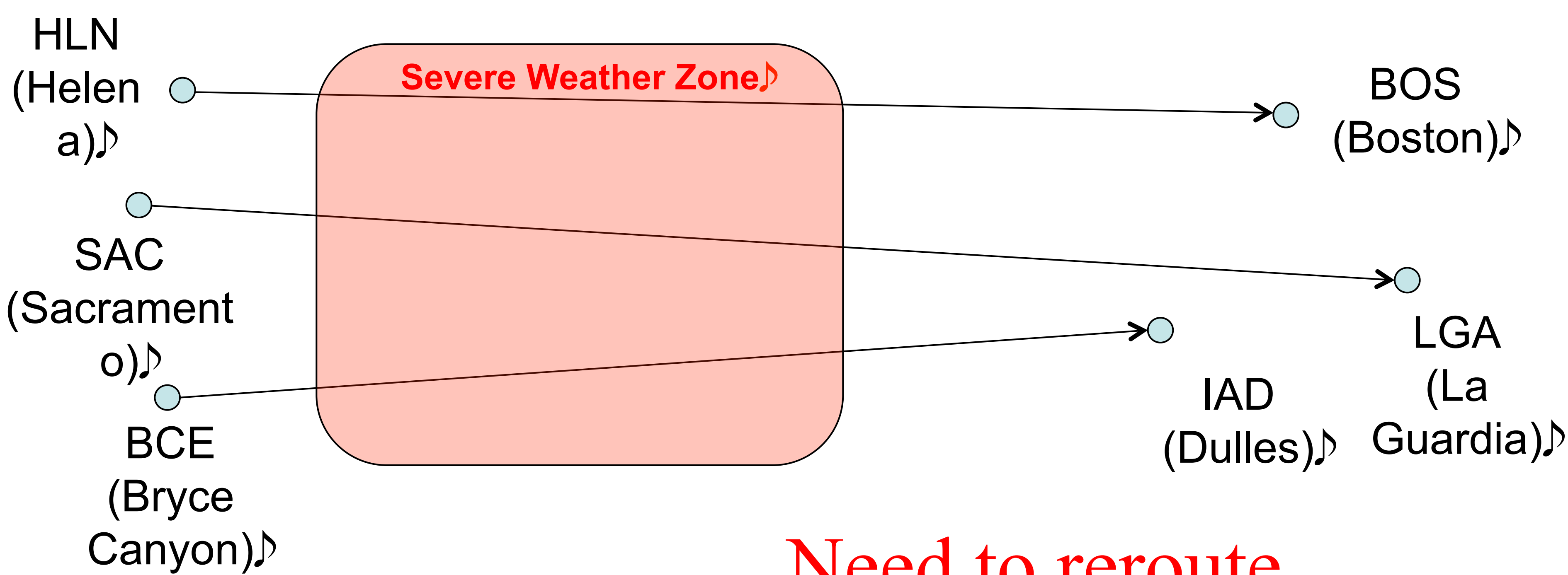
- Capacity Loss causing delays

Capacity Loss: Consider an Example



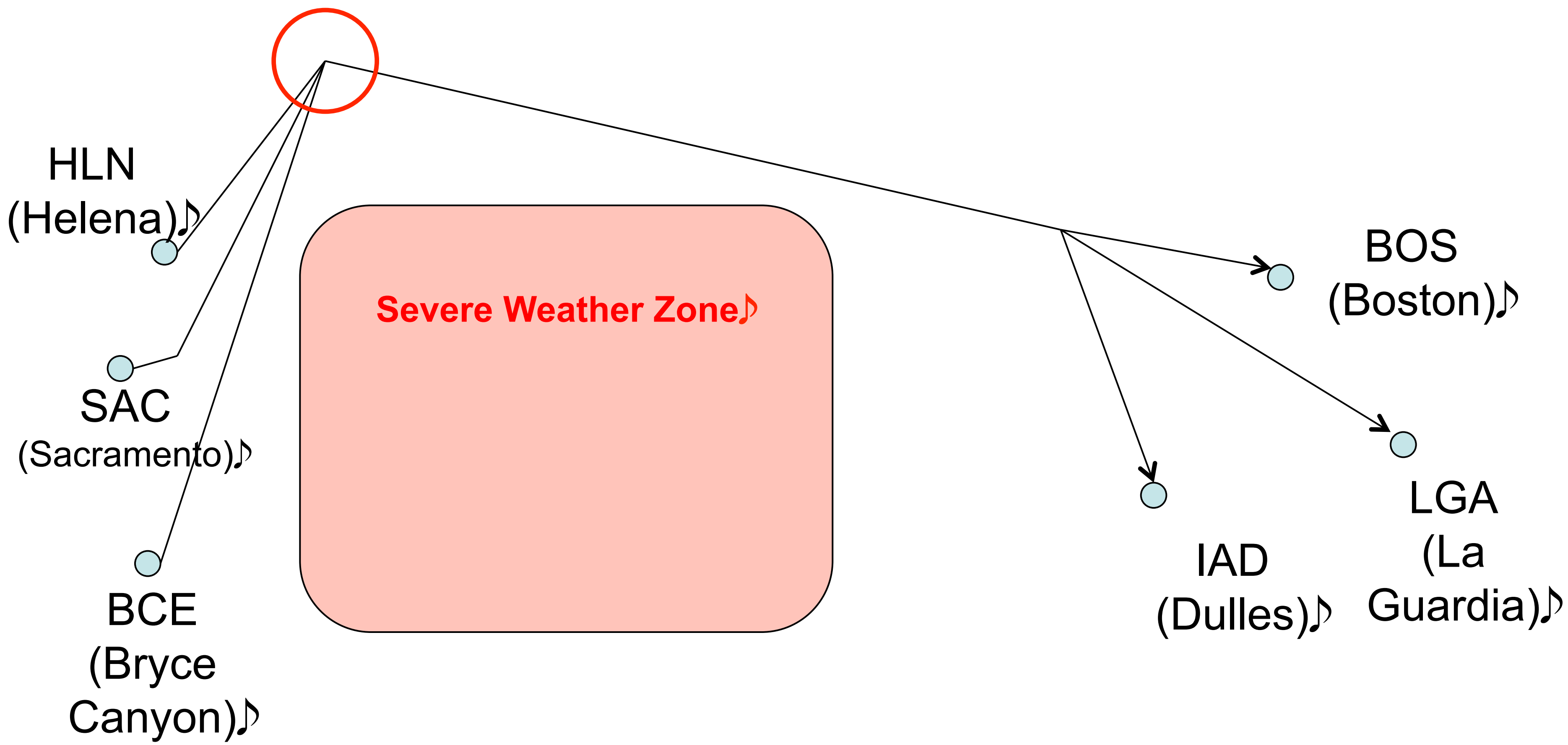
Ref. Sridhar, B., Grabbe, S.R., and Mukherjee, A. Modeling and optimization in traffic flow management *“Watertown Example”, Proc. of the IEEE*, 96(12), 2060–2080.

Assume Severe Weather occurs



Need to reroute

Severe weather Rerouting



Current rerouting has merges: Why? Simpler

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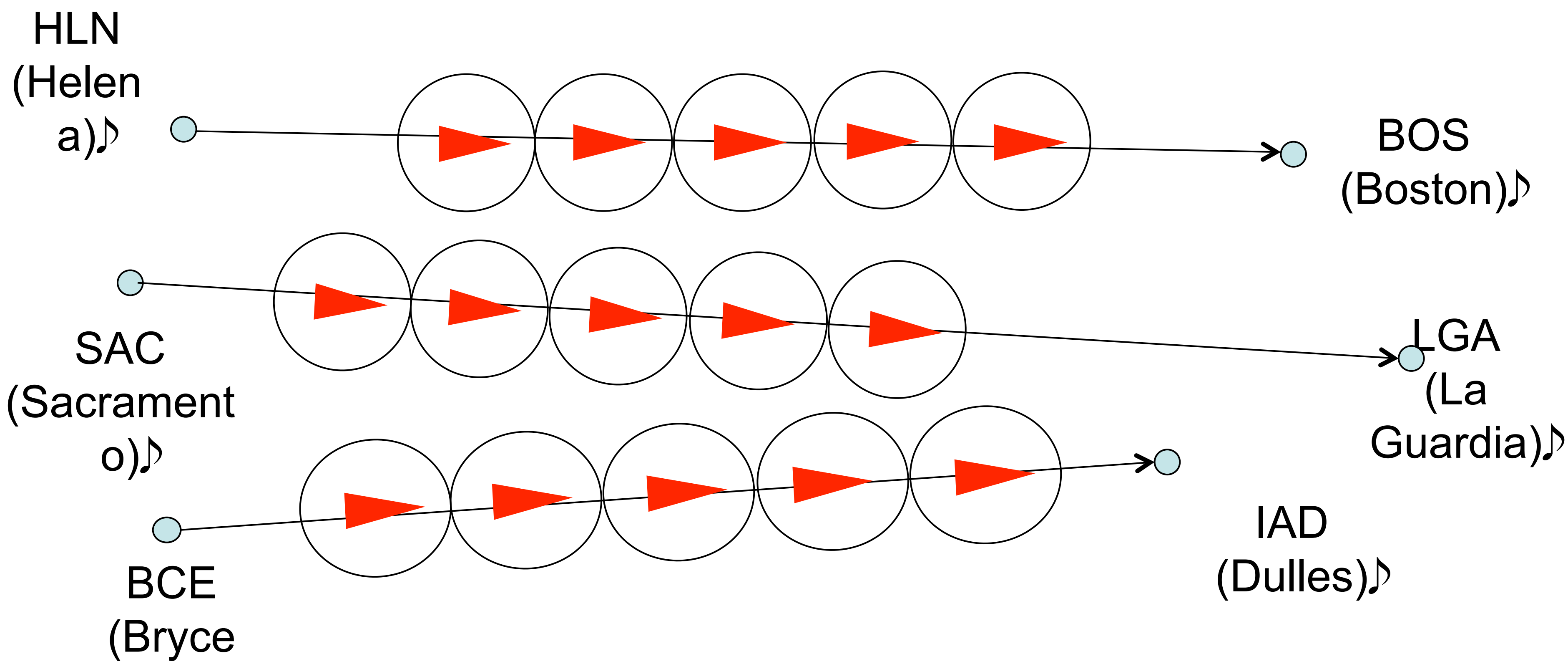
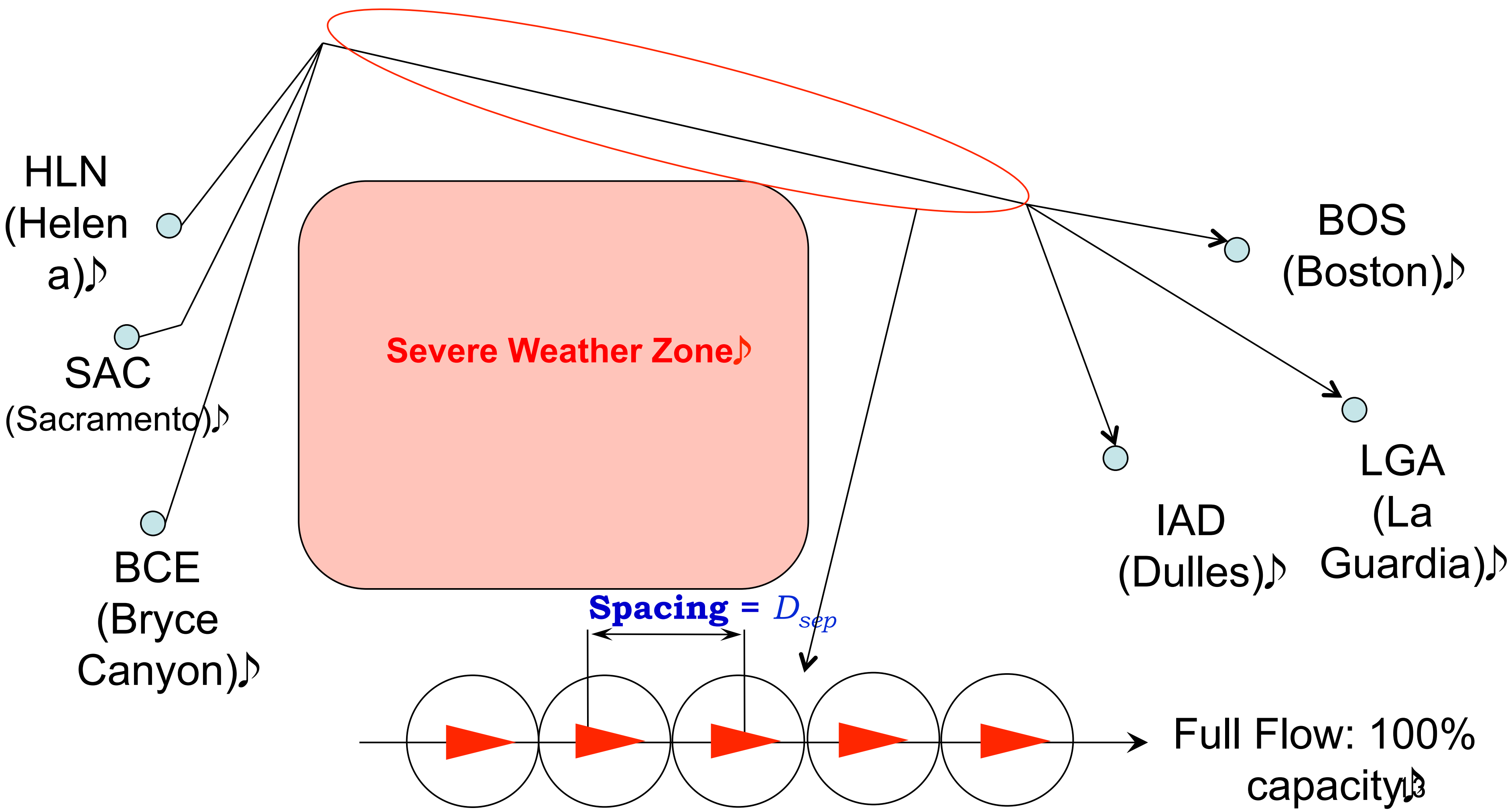
Max Flow Capacity Before Merging

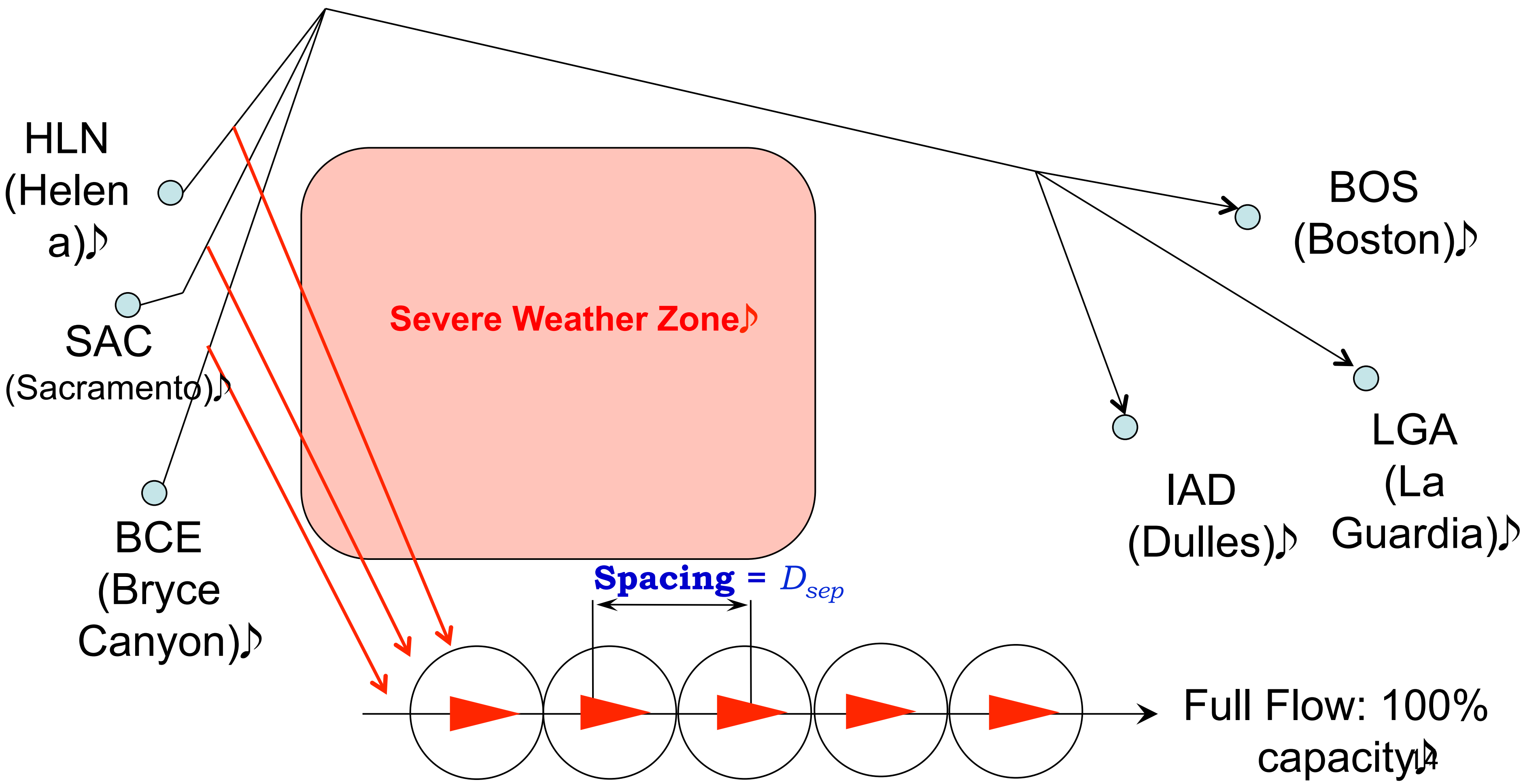


Ref. Sridhar, B., Grabbe, S.R., and Mukherjee, A. Modeling and optimization in traffic flow management *"Watertown Example", Proc. of the IEEE*, 96(12), 2060–2080.

Lets say the new merged route has maximum flow capacity

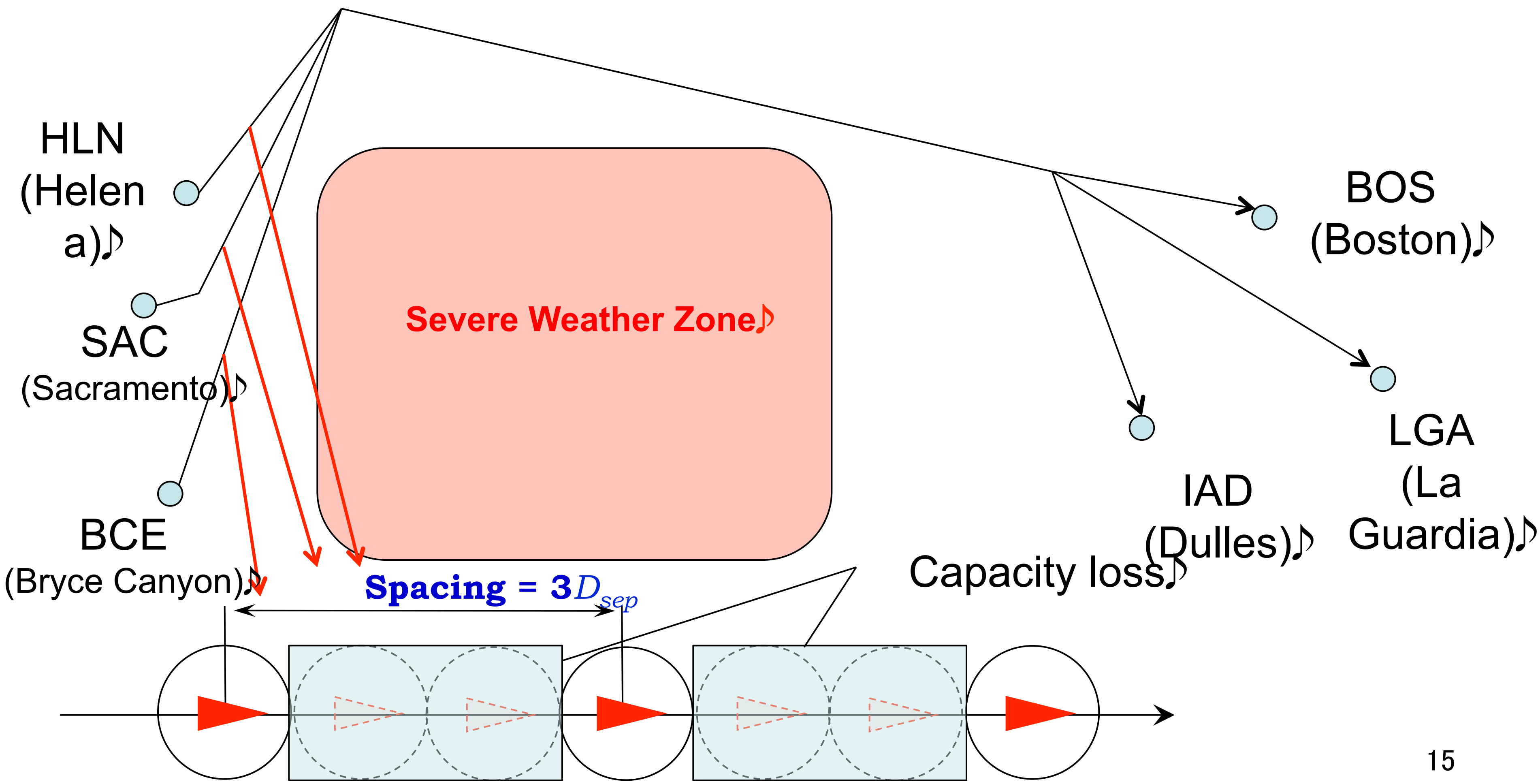


Then each of the input routes cannot have max capacity



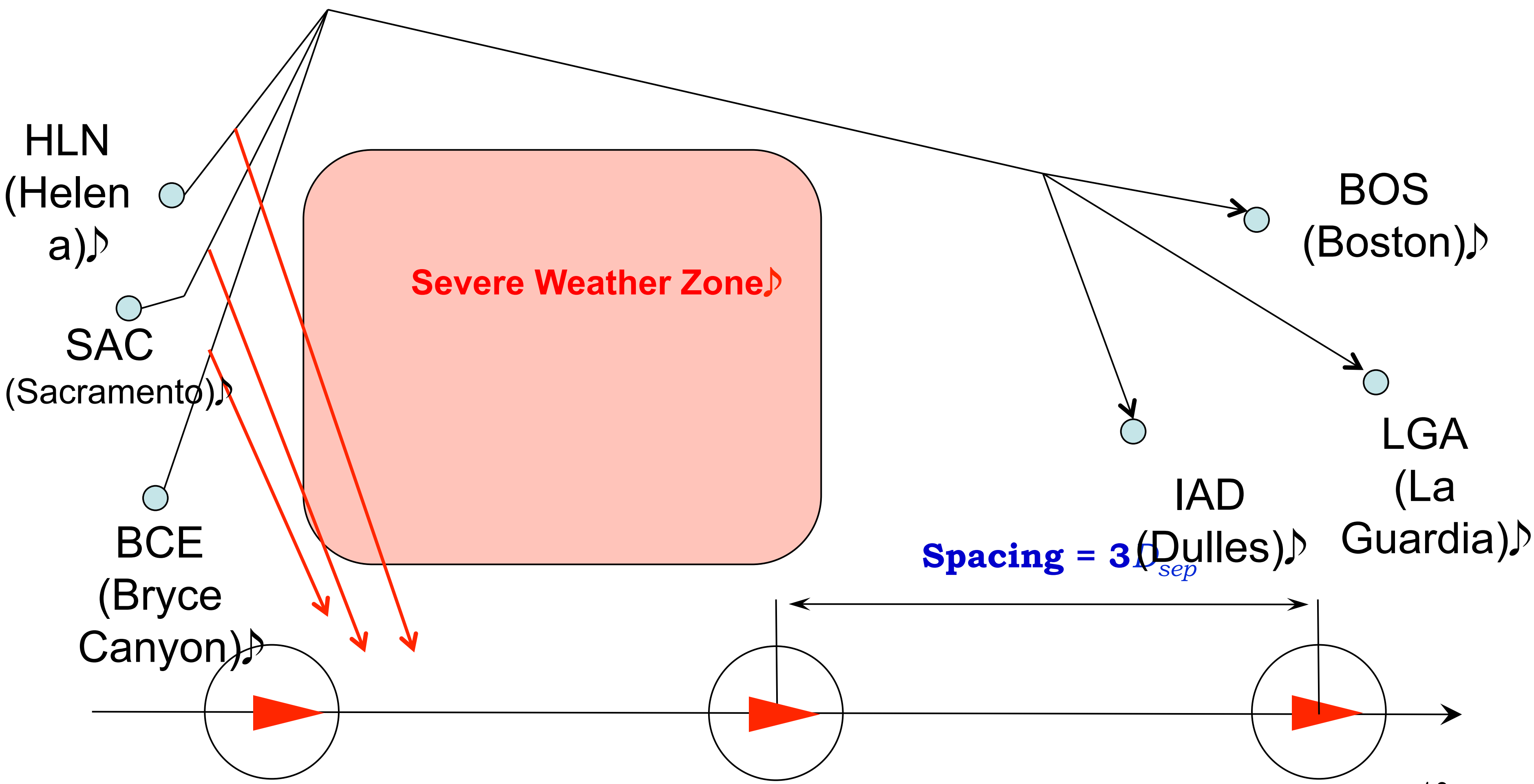
Problem: No space available for merging to happen

Capacity loss occurs leads to rescheduling and delays



Assuming constant spacing, 1/3 of full capacity for merge to be available

Would prefer no capacity loss!



Is this possible? Should be – lots of space is available!

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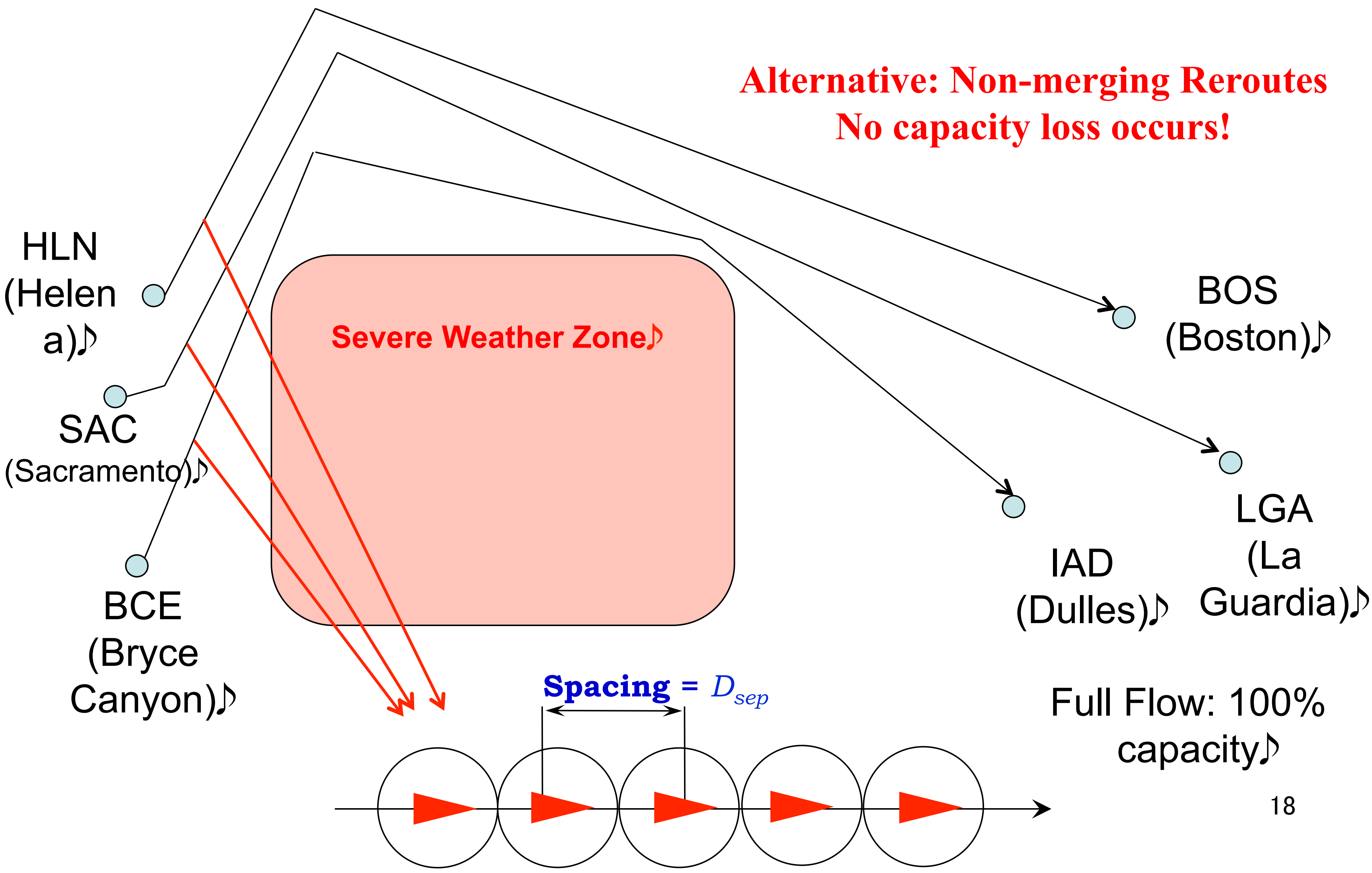
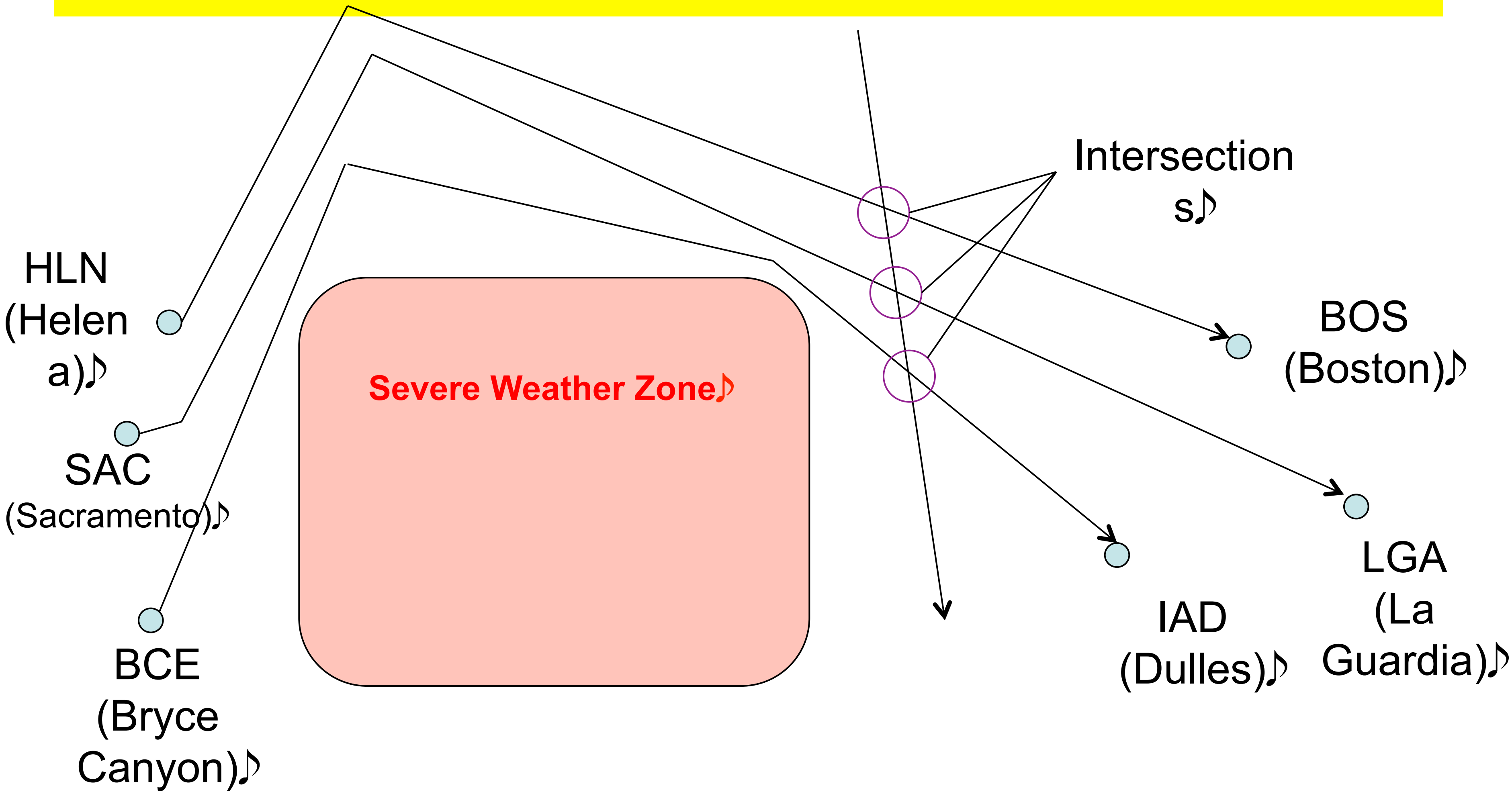
Reroute alternative without loss of capacity



Problems with alternate rerouting



More intersections- More potential for conflicts… more complex ATC --- Need to develop en-route conflict resolution procedure

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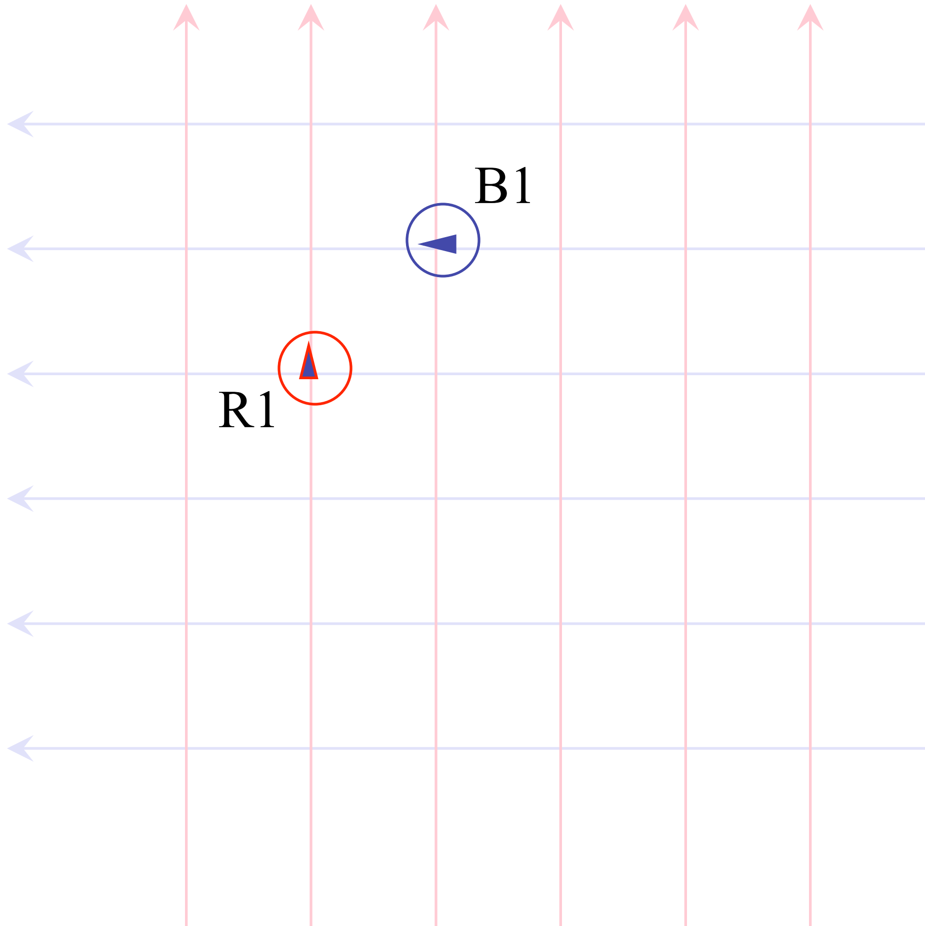
Decentralized CRP Design Issues

1. Avoid domino effects → no new conflicts
2. Decentralized CRP → local in space and time
3. Guarantee Stability

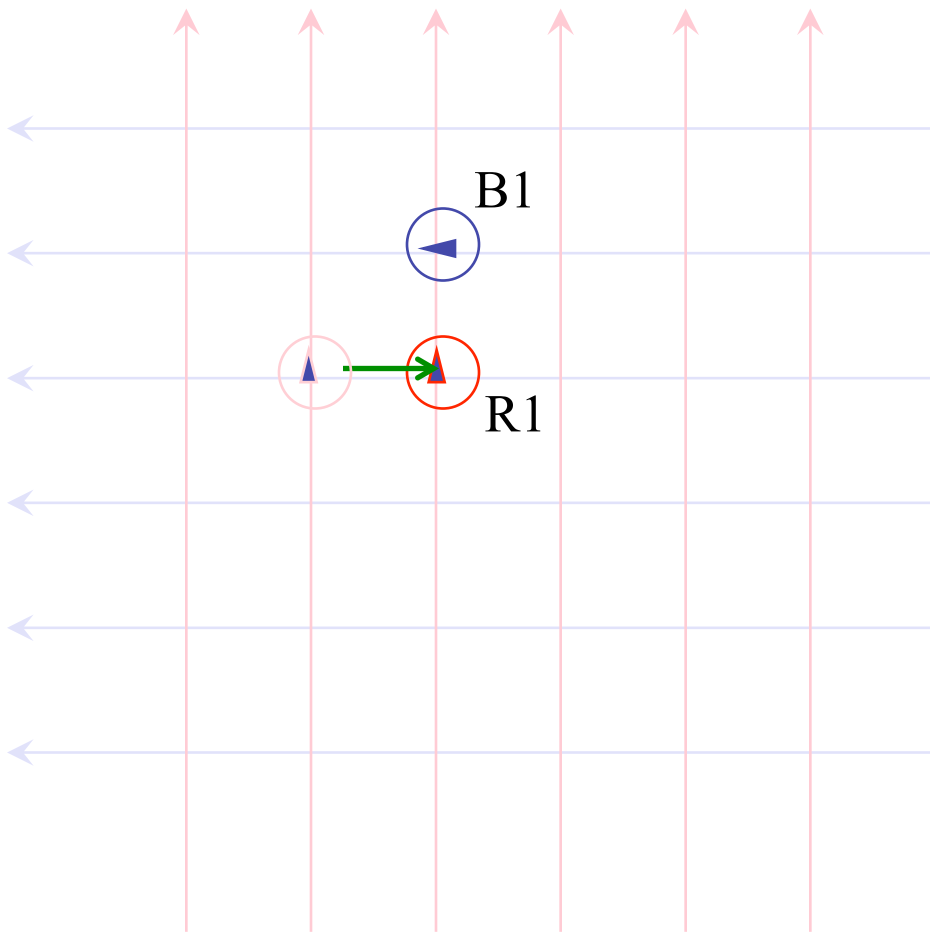
Issue 1: Avoid domino effects



R1 & B1 in conflict

Resolution of one conflict creates another and so on…

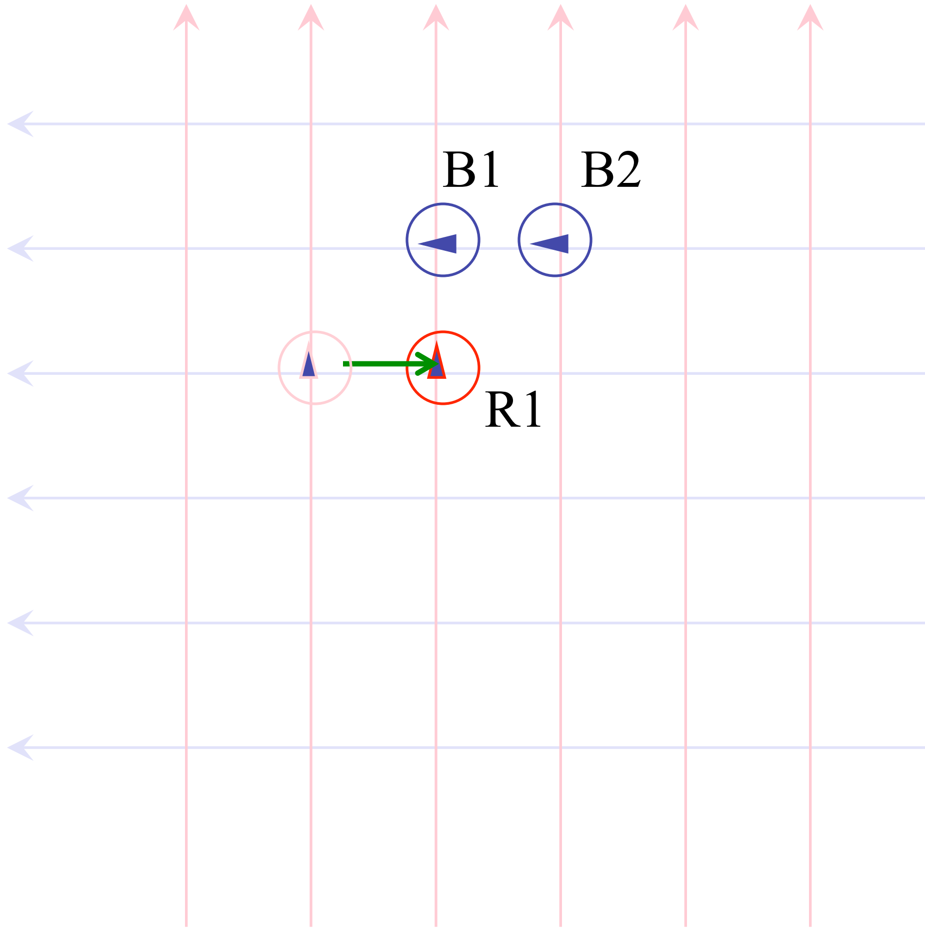
Conflict resolution



R1 shifted

Resolve conflict by shift operation (Mao, Feron, et. al.)

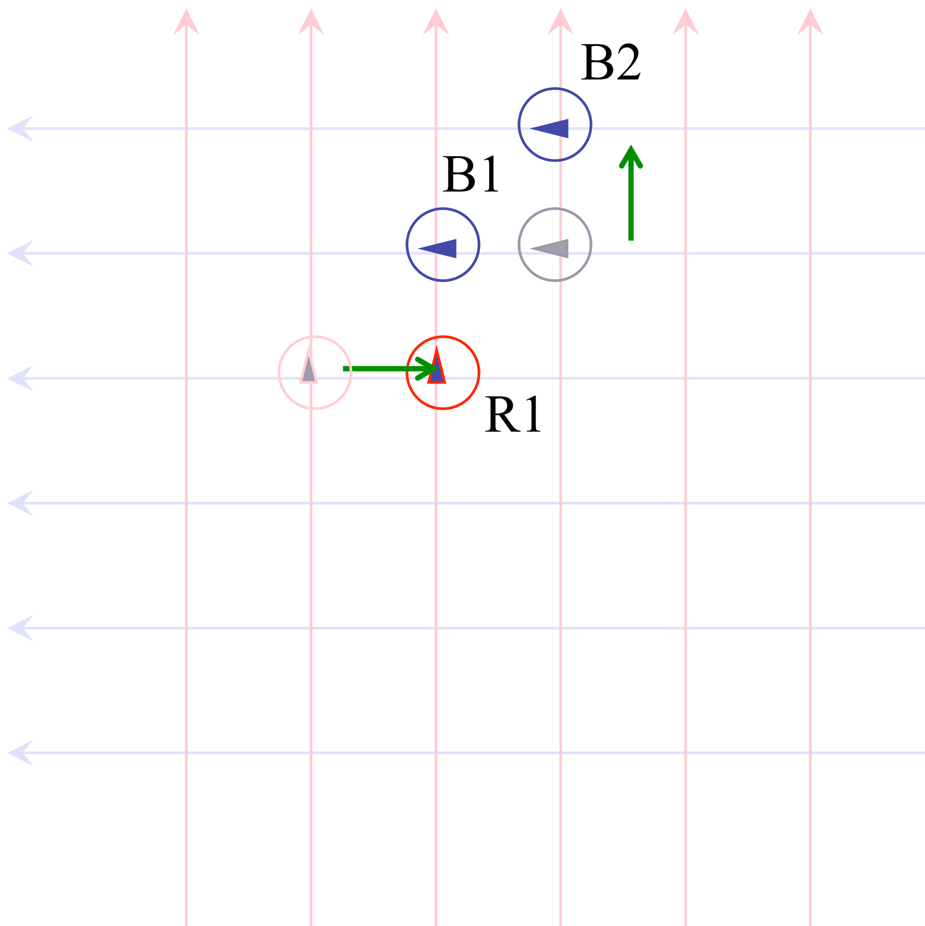
Potential for new conflicts



R1 & B2 in conflict

Resolve conflict by shift operation (Mao, Feron, et. al.)

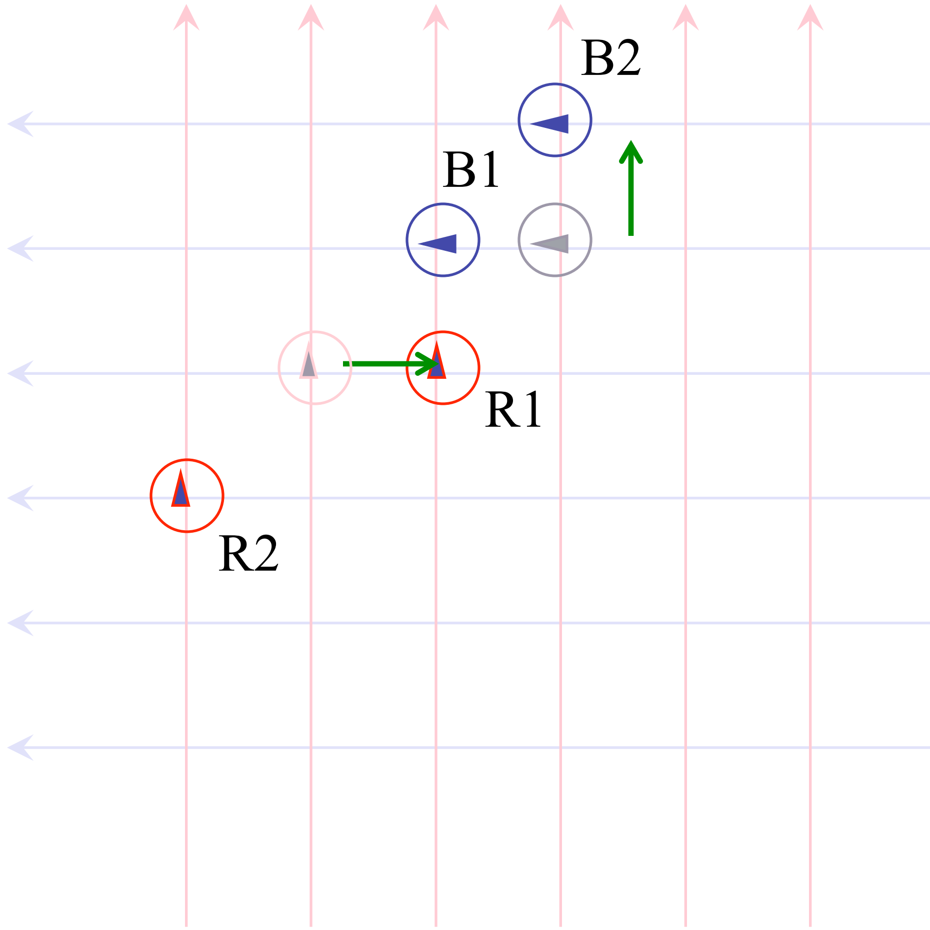
Potential new conflicts



B2 shifted

Resolve conflict by shift operation again…

Leads to another conflict and so on…



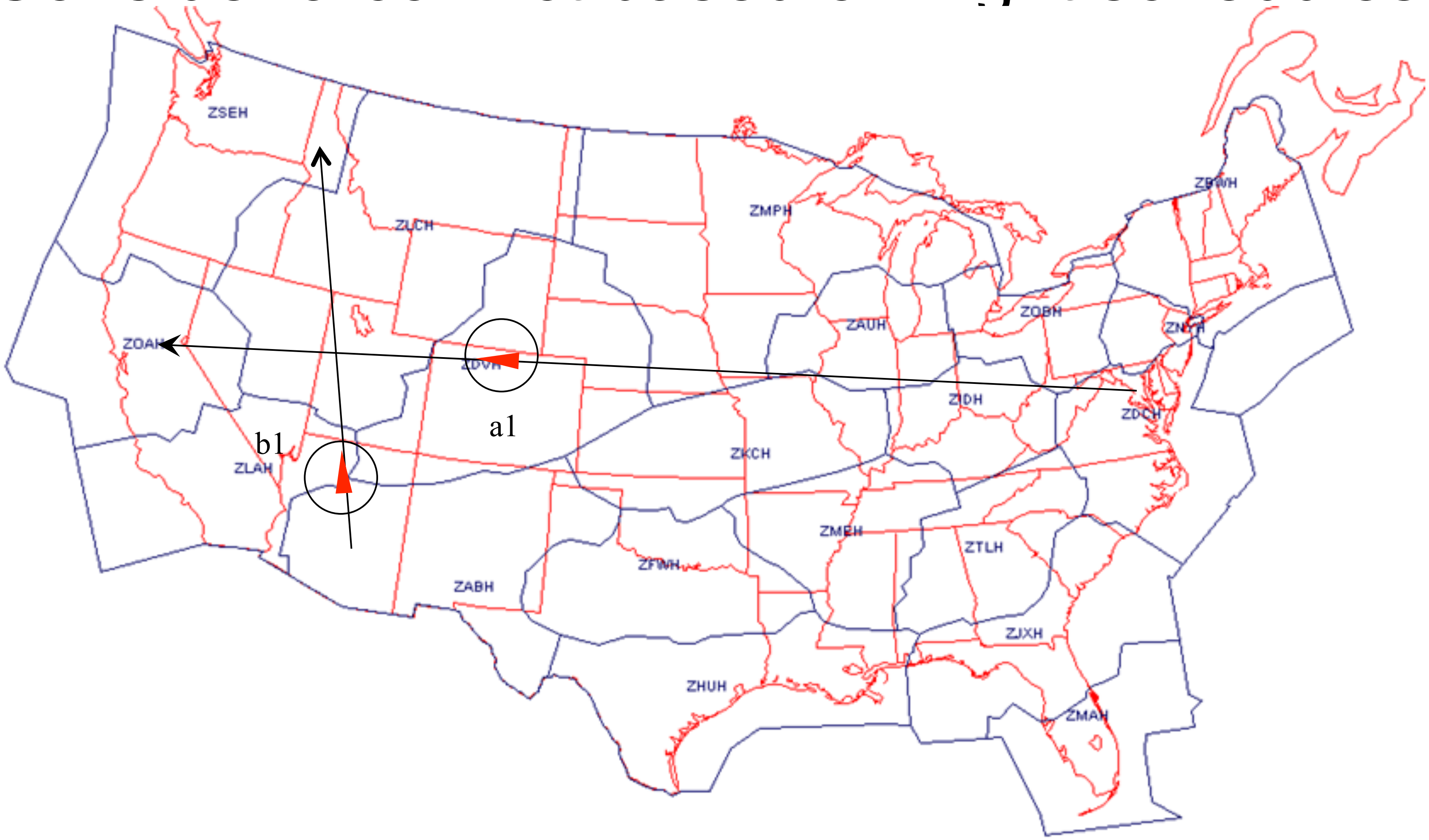
R2 & B2 in conflict

Such domino effects needs to be avoided --- no new conflicts

Issue 2: Decentralized CRP

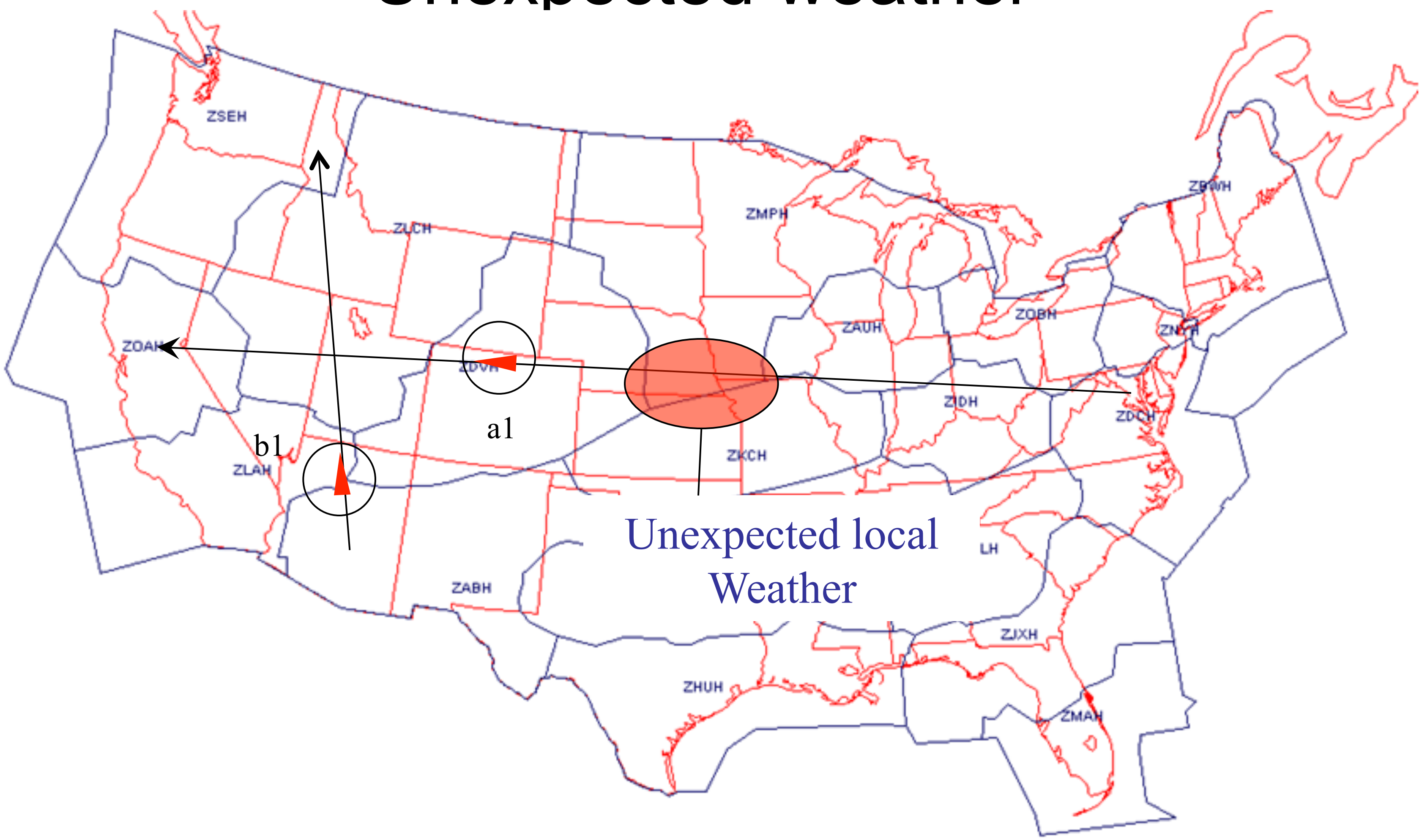
Uncertainties (weather, missed departure slots etc.) implies that when a conflict occurs cannot be predicted ahead of time

Consider a conflict based on flight schedules



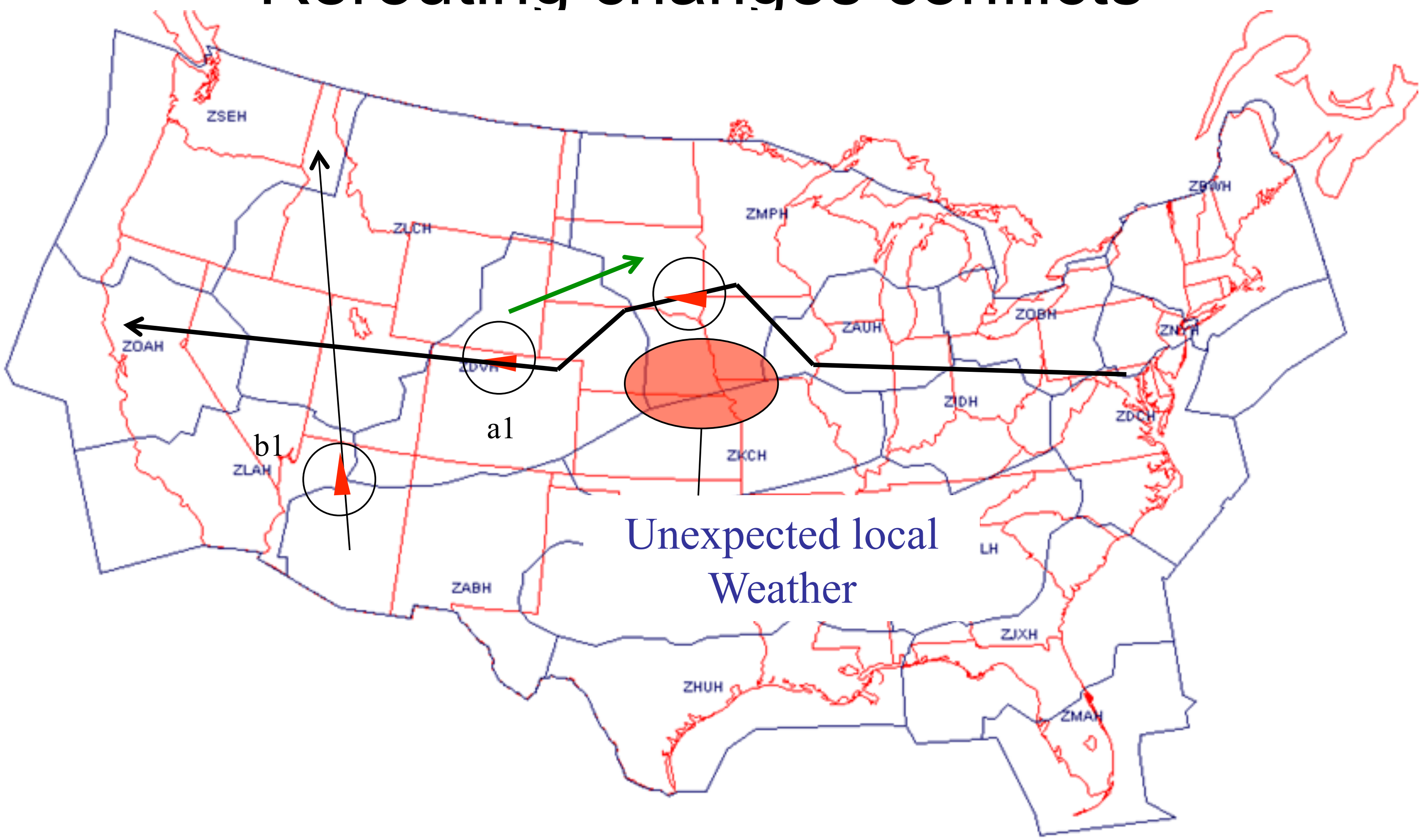
A flight across US can take 4-5 hours
local weather can change in a couple of hours

Unexpected weather



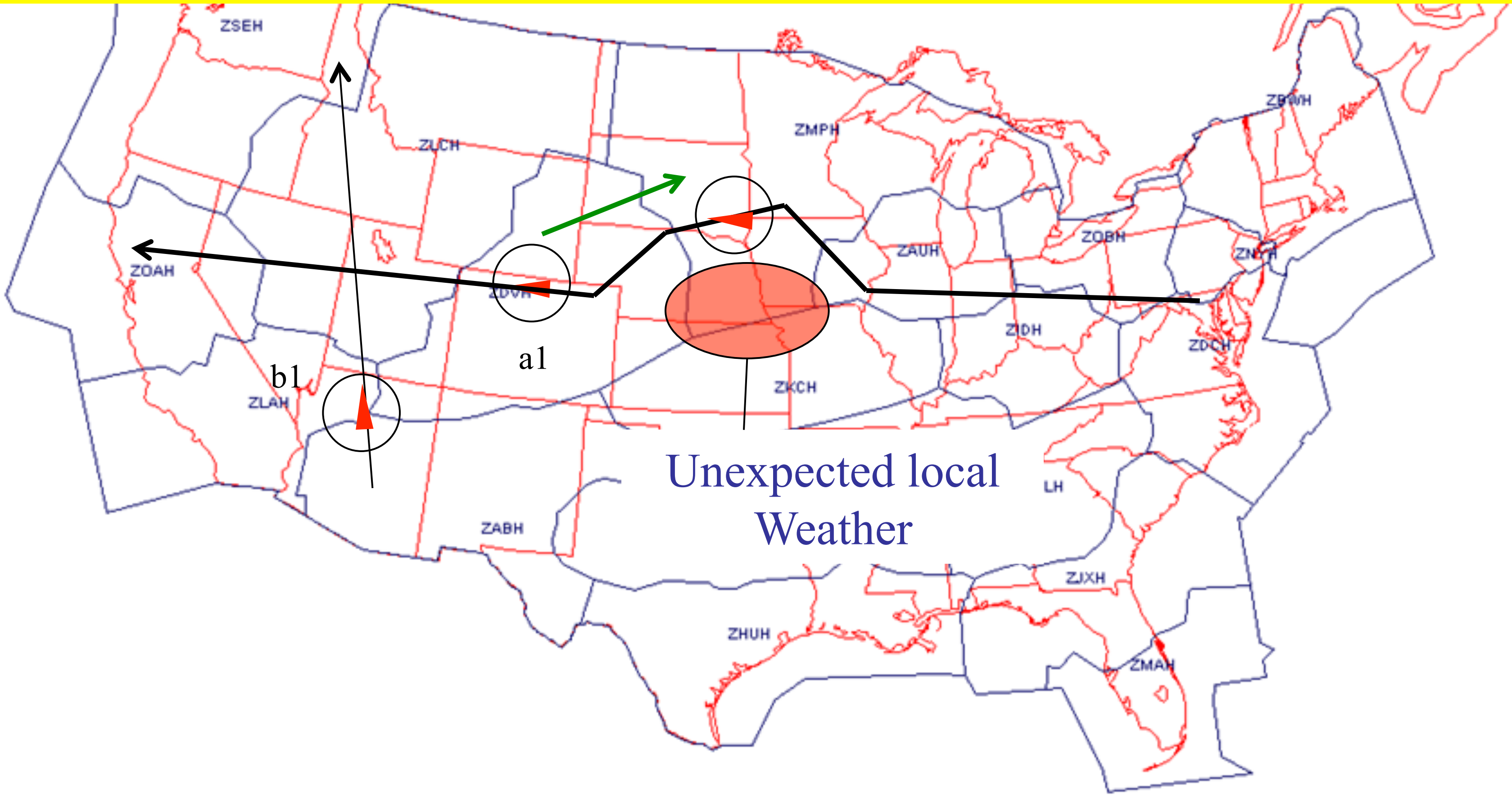
Need for rerouting around weather

Rerouting changes conflicts



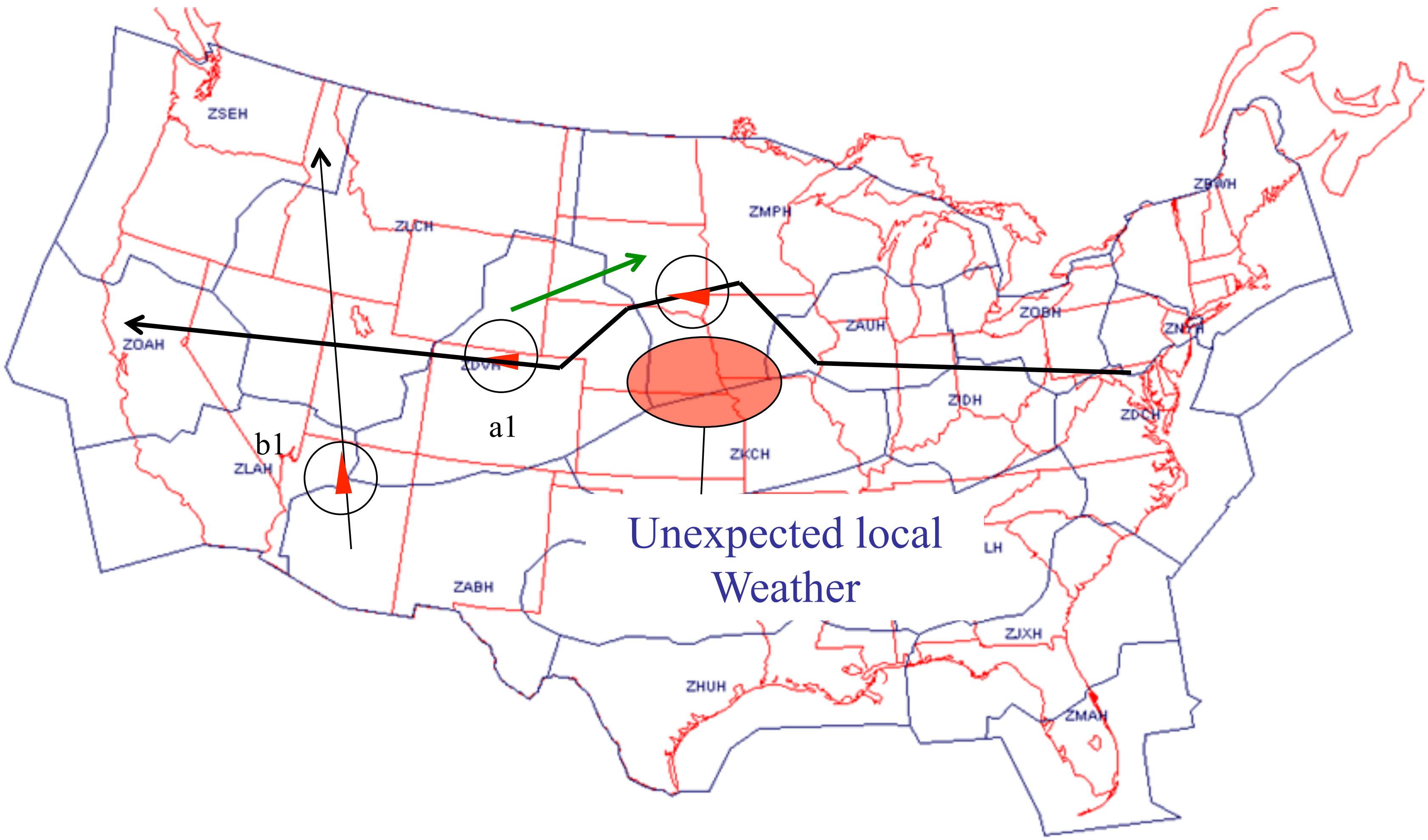
Rerouting around the weather will delay flights and alter the potential for conflicts (new and old conflicts)

Prediction of future conflicts has uncertainty



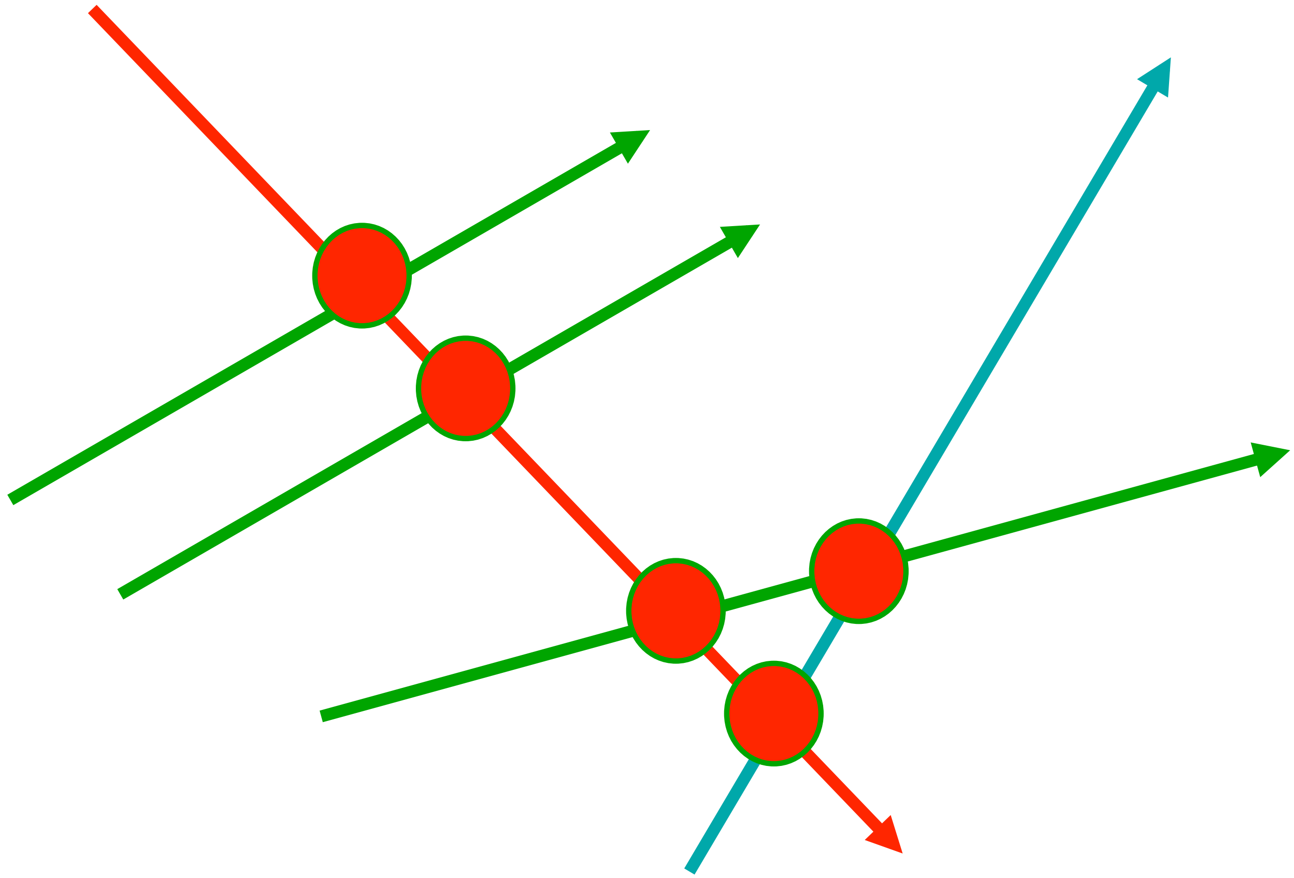
Conflict prediction and resolution needs to be local (spatially and temporarily)

CRP has to be decentralized!



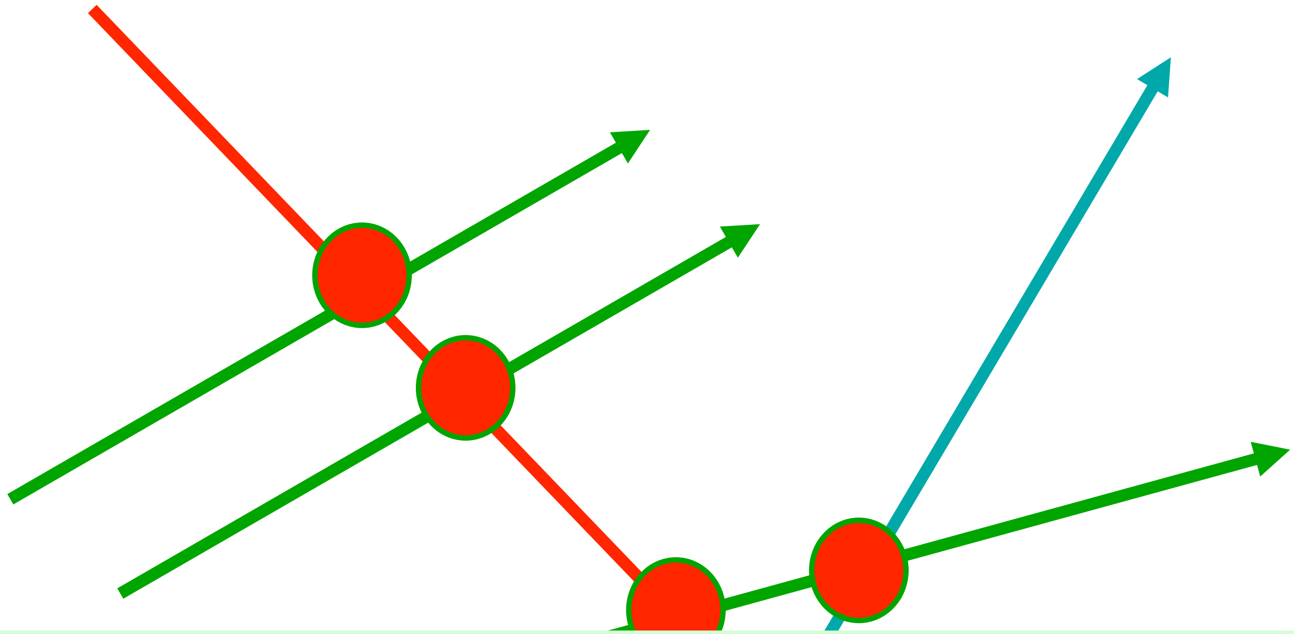
Conflict prediction and resolution needs to be local (spatially and temporarily)

Decentralized conflict resolution?



Is this possible?

Decentralized conflict resolution?



Is this possible?

YES

Done currently! But inefficient (lots and lots of buffers) and not flexible (difficulty to train controllers with new schemes)

Need to understand Limits of decentralized CRP

Issue 3: Guaranteed CRP stability

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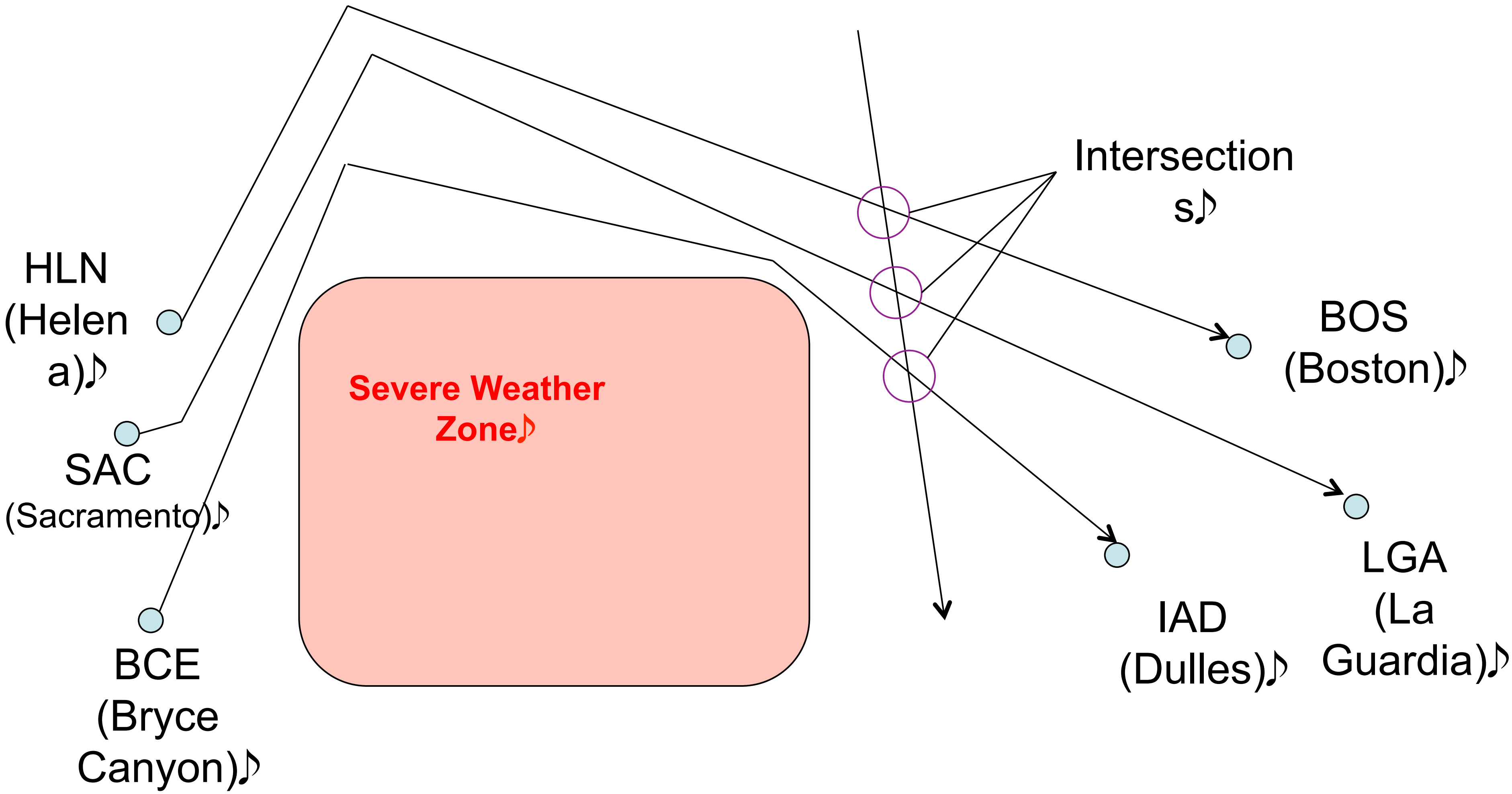
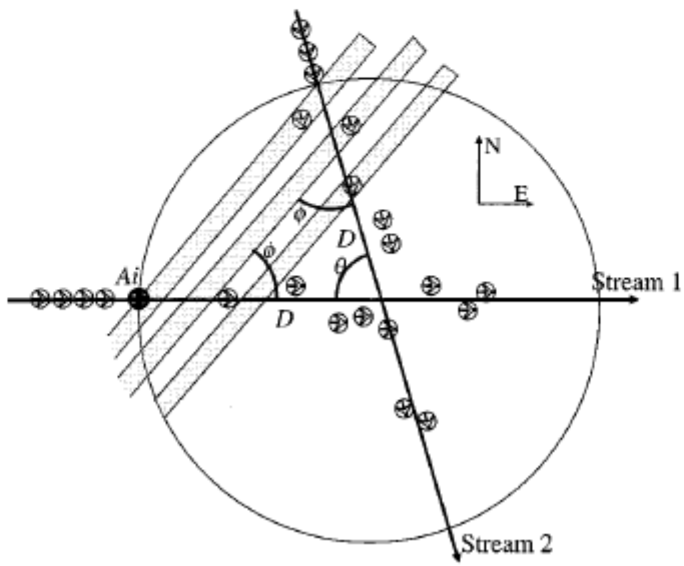


Critical for design of automation procedures, e.g., to help with complex rerouting around adverse weather.

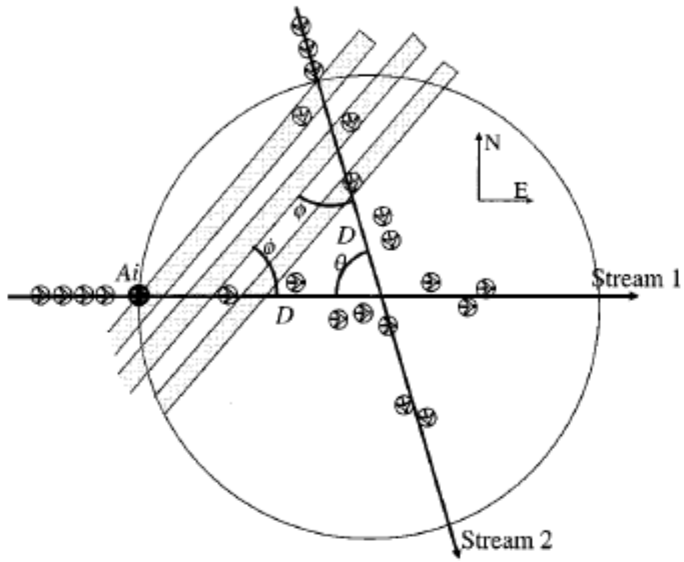
Previous works study such stability issues



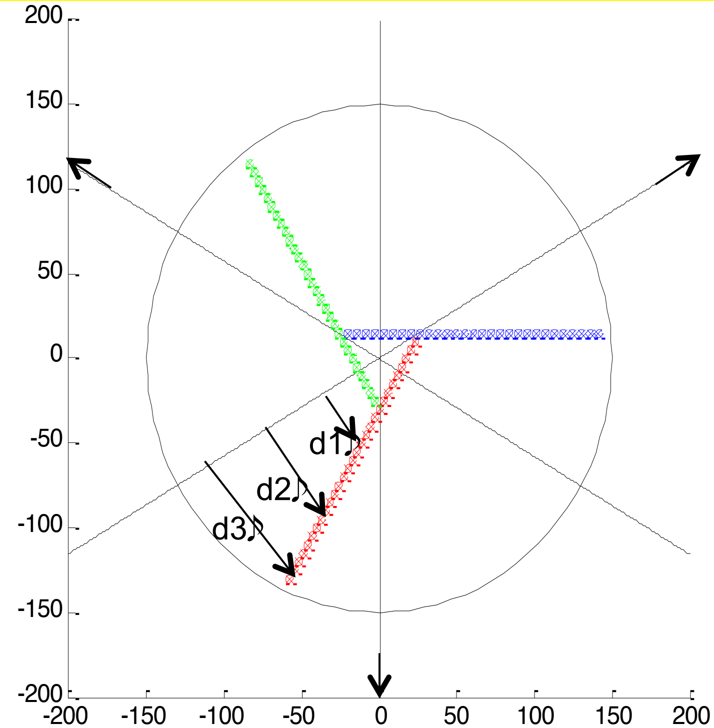
Can guarantee for general 2-flow intersections

Reference: Stability and Performance of Intersecting Aircraft Flows Under Decentralized Conflict Avoidance Rules, Mao, Feron, Bilimoria, 2001

Stability cannot be guaranteed always…



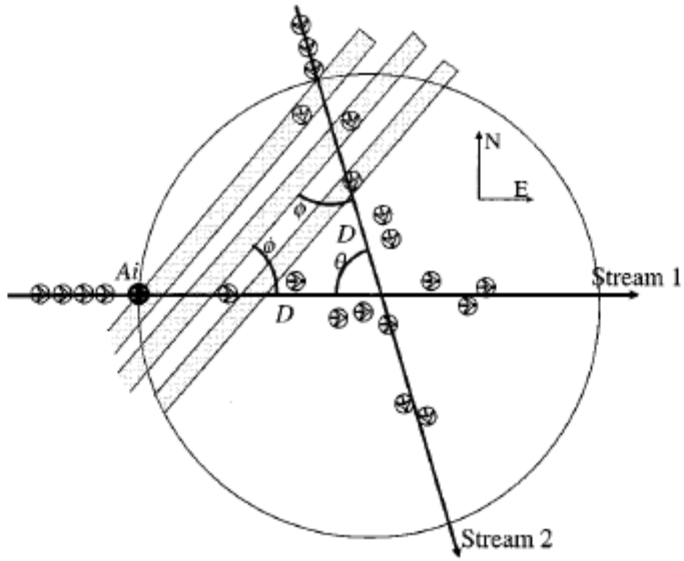
Can guarantee for general 2-flow intersections



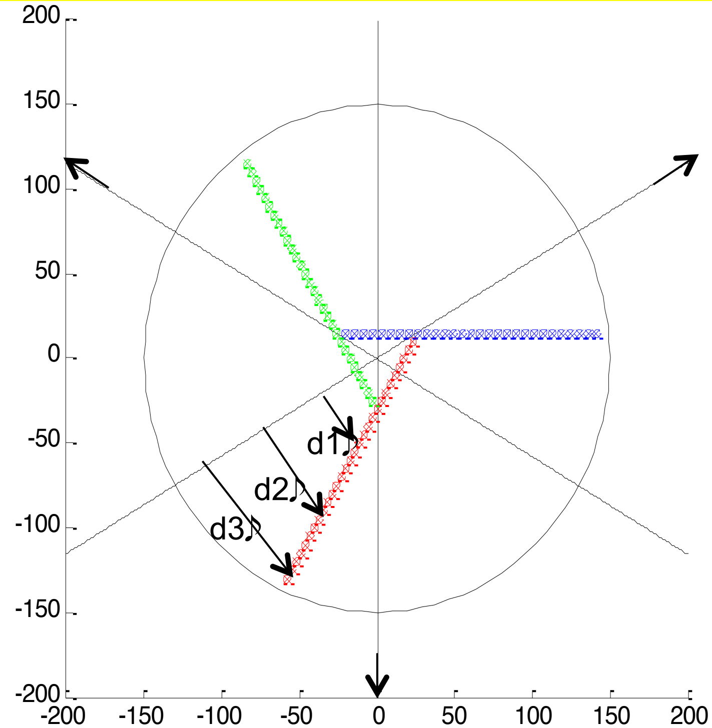
Generic algorithms are not stable as shown by Mao, Feron, et. al. for a 3-flow intersection

Reference: Stability and Performance of Intersecting Aircraft Flows Under Decentralized Conflict Avoidance Rules, Mao, Feron, Bilimoria, 2001

Stability cannot be guaranteed always…



Can guarantee for general 2-flow intersections



Generic algorithms are not stable as shown by Mao, Feron, et. al.

Guaranteed stability critical for automation…

Recap: Decentralized CRP Design Issues

1. Avoid domino effects → decoupled CRPs
2. Decentralized CRP → local in space and time
3. Guarantee Stability

We have a CRP design that addresses these issues

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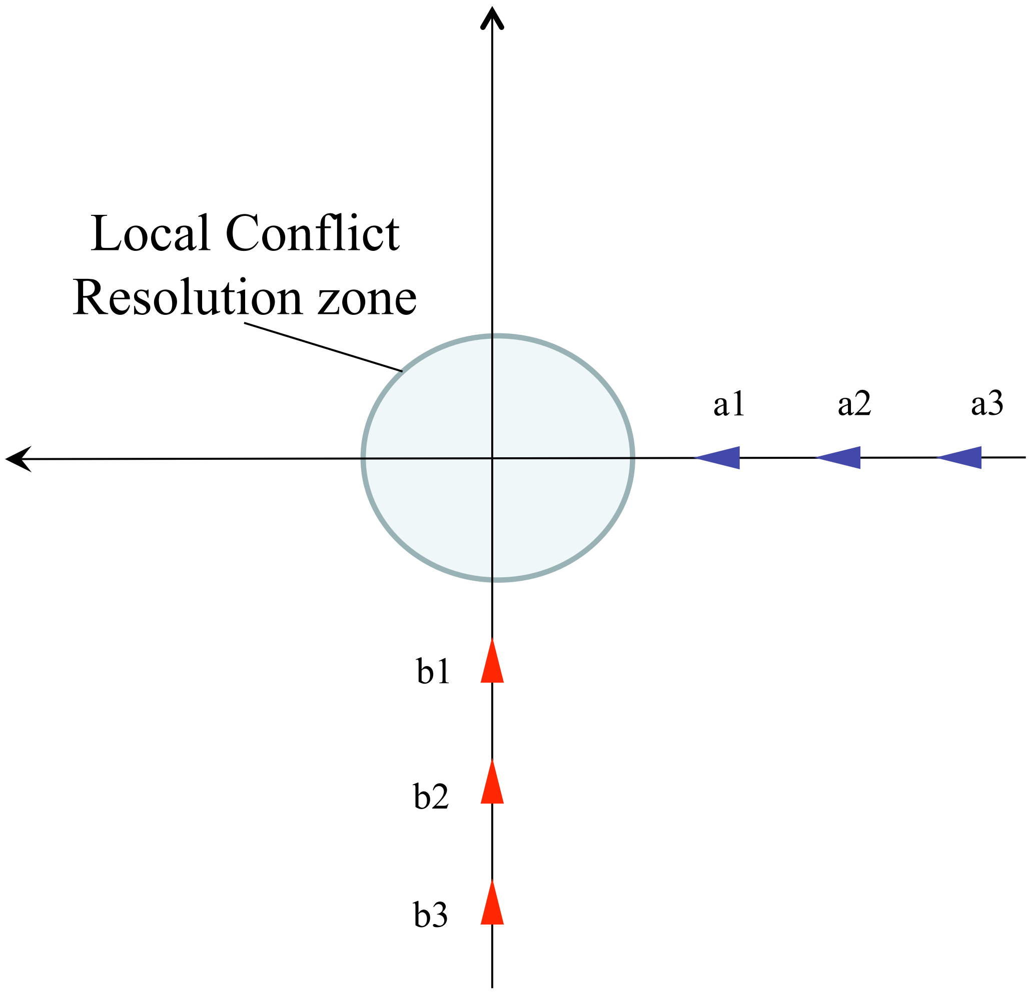
Required Properties of local CRP to enable

1. Avoid domino effects → decoupled; no additional conflicts
2. Decentralized CRP → local in space and time
3. Guarantee Stability

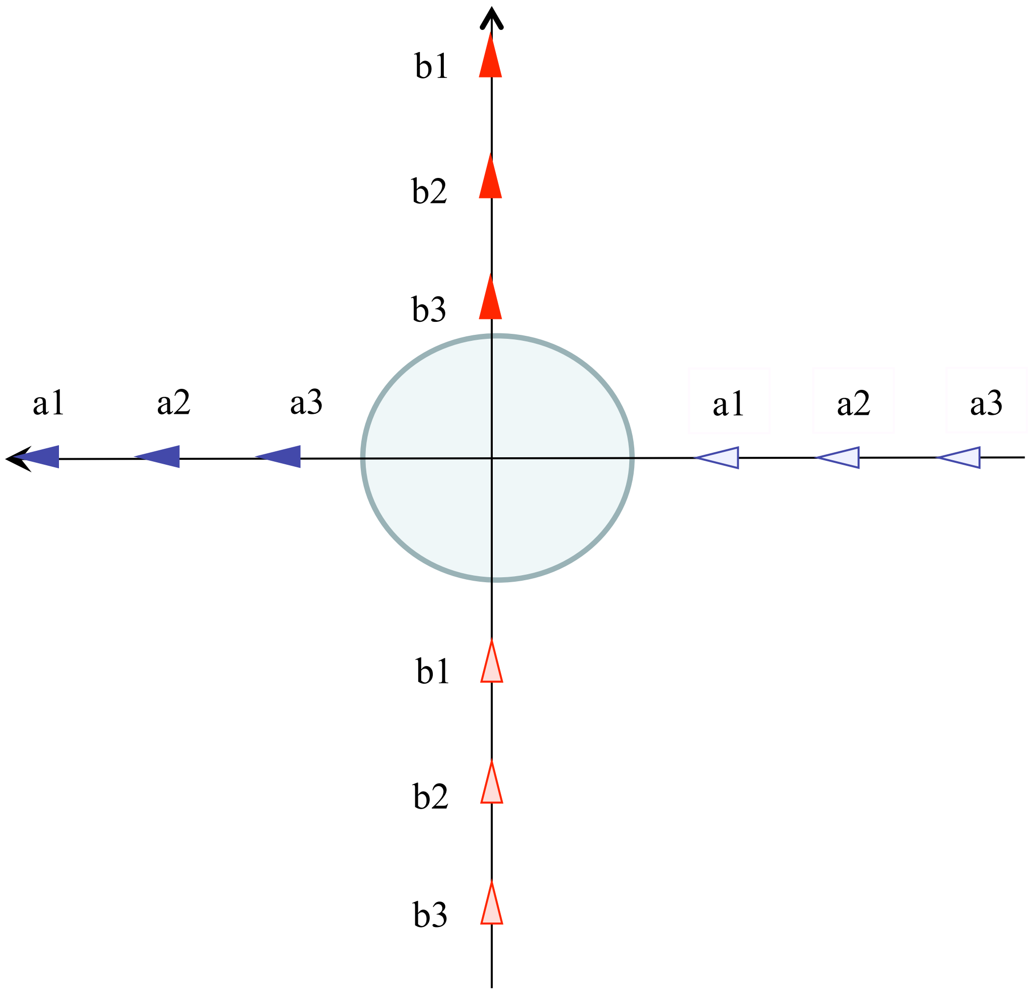
Reference: S. Devasia, D. Iamratanakul, G. Chatterji, and G. Meyer "Decoupled Conflict-Resolution Procedures for Decentralized Air Traffic Control." *IEEE Transactions on Intelligent Transportation Systems*, Vol. 12 (2), pp. 422-437, June 2011.

Main properties of local CRP



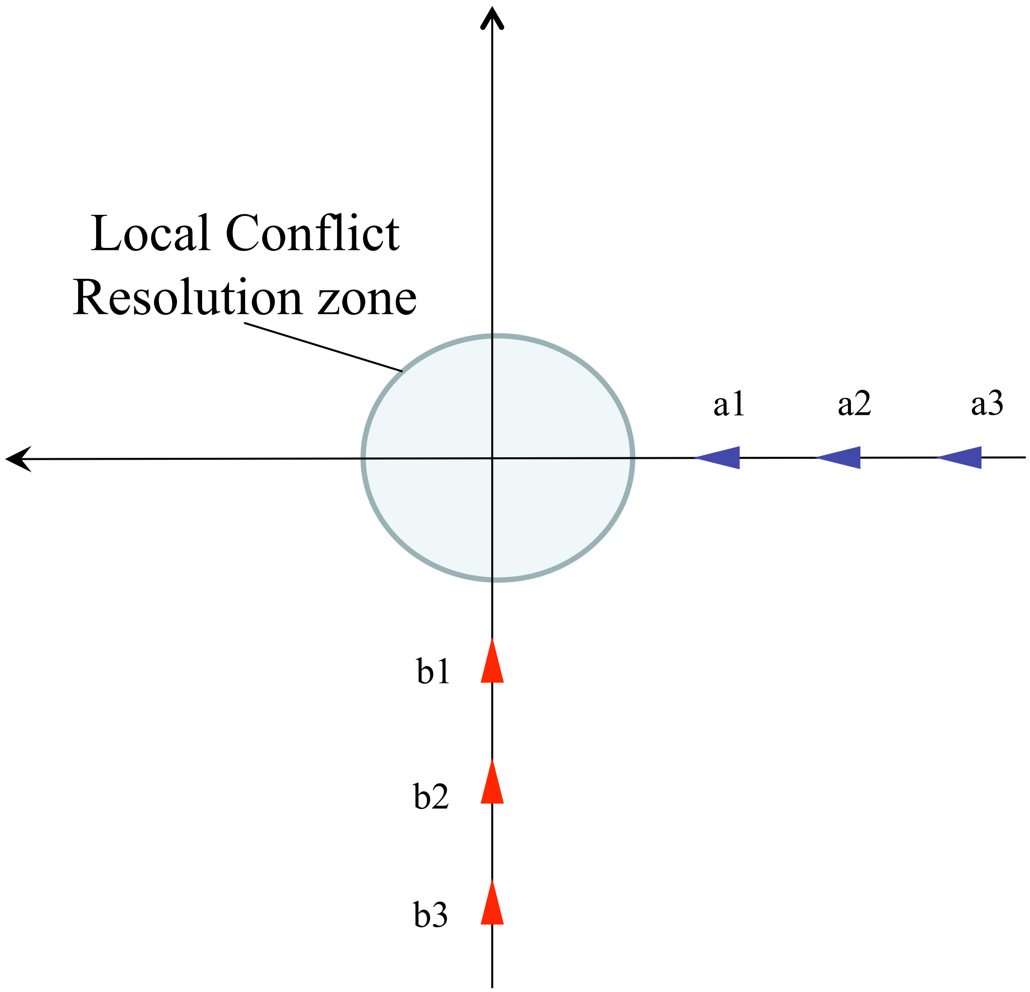
- Local CRP bounded in space and time & returns to original path

Main properties of local CRP



- Local CRP bounded in space and time & returns to original path
- **Arrival sequence = exit sequence (in each route)**
- **basic idea is to use equal length paths for all aircraft**

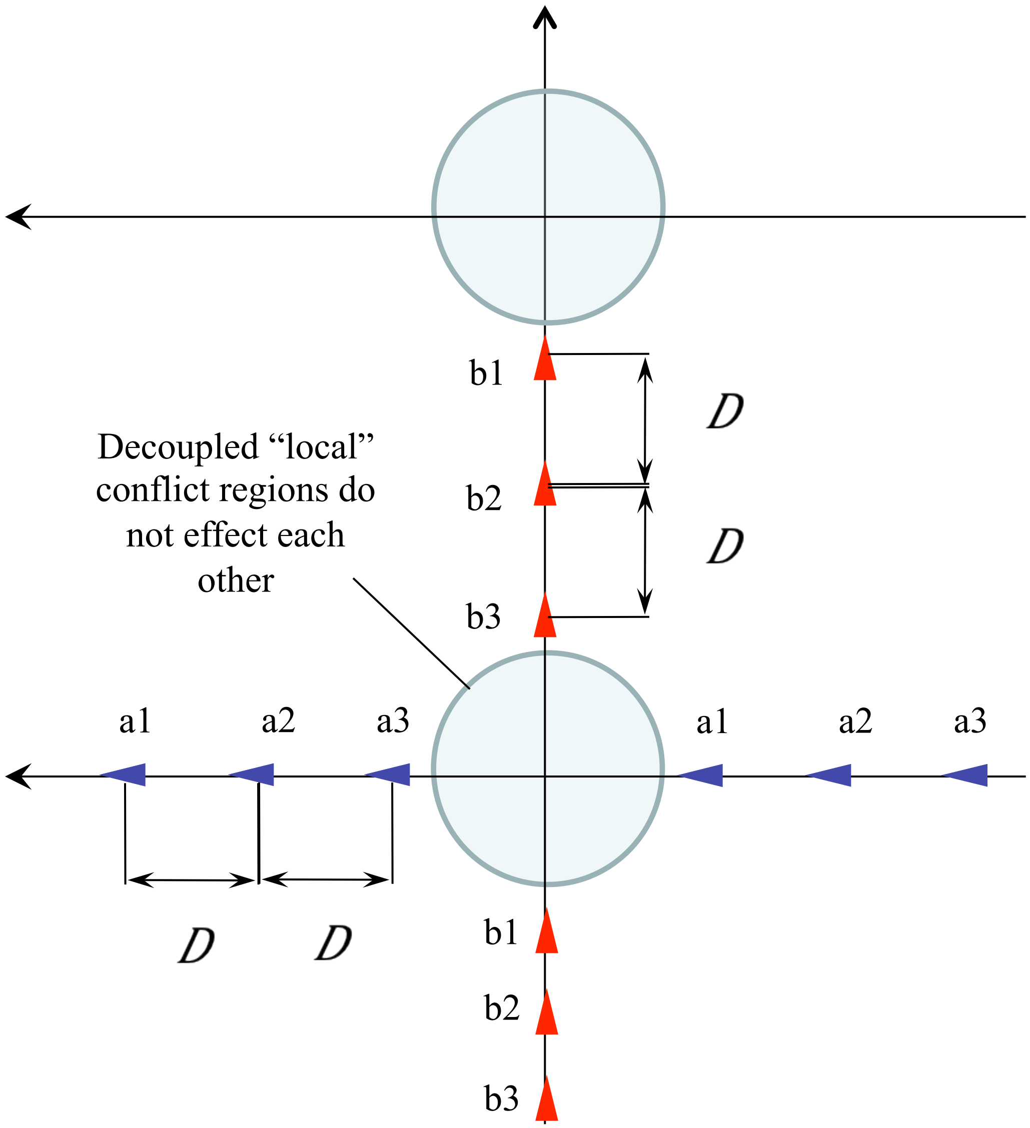
Main properties of local CRP



- Local CRP bounded in space and time & returns to original path
- Arrival sequence = exit sequence

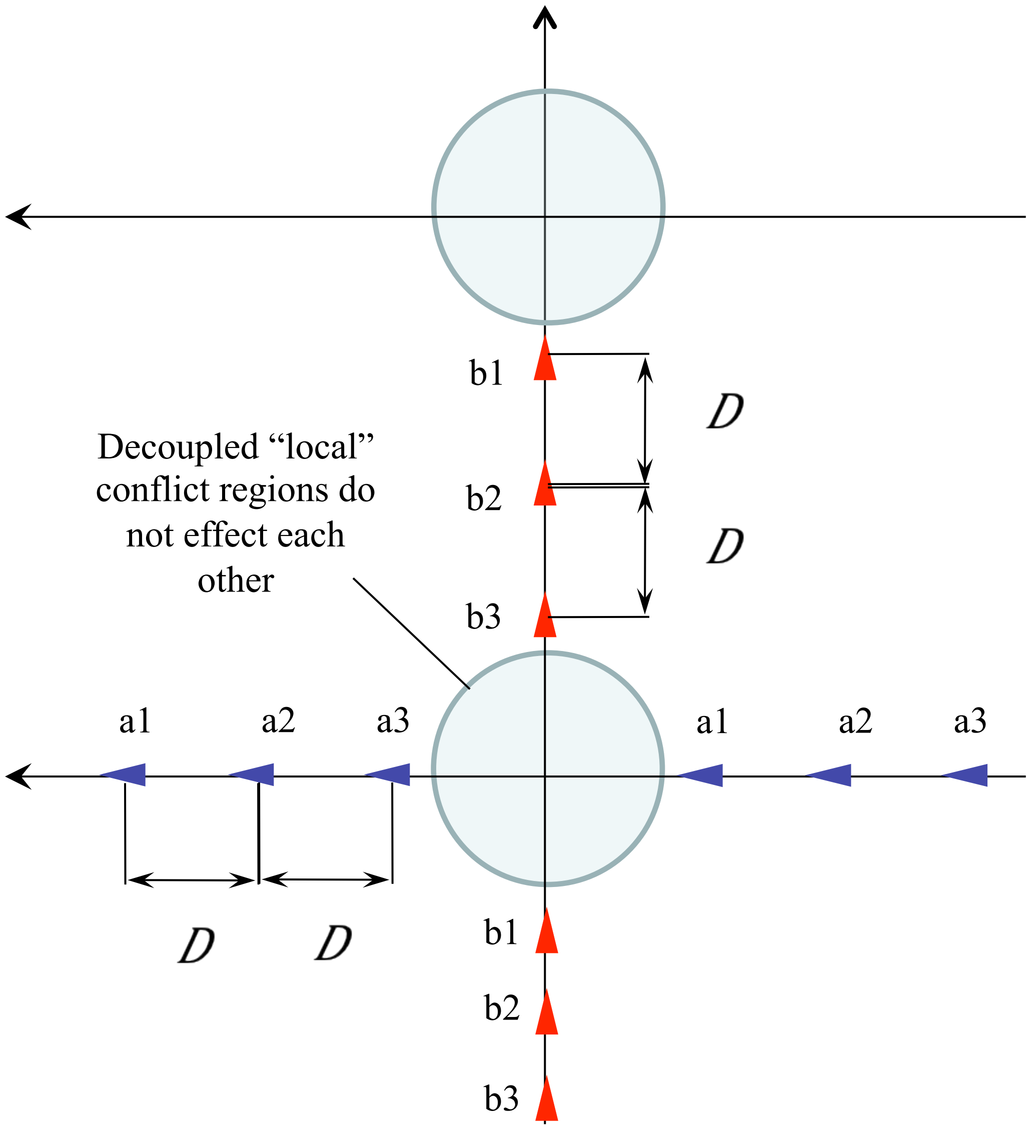
- **Claim --- yields decoupled, decentralized, guaranteed resolution (if conflicts are sufficiently sparse)**

Solution to Issue 1- Domino Effect



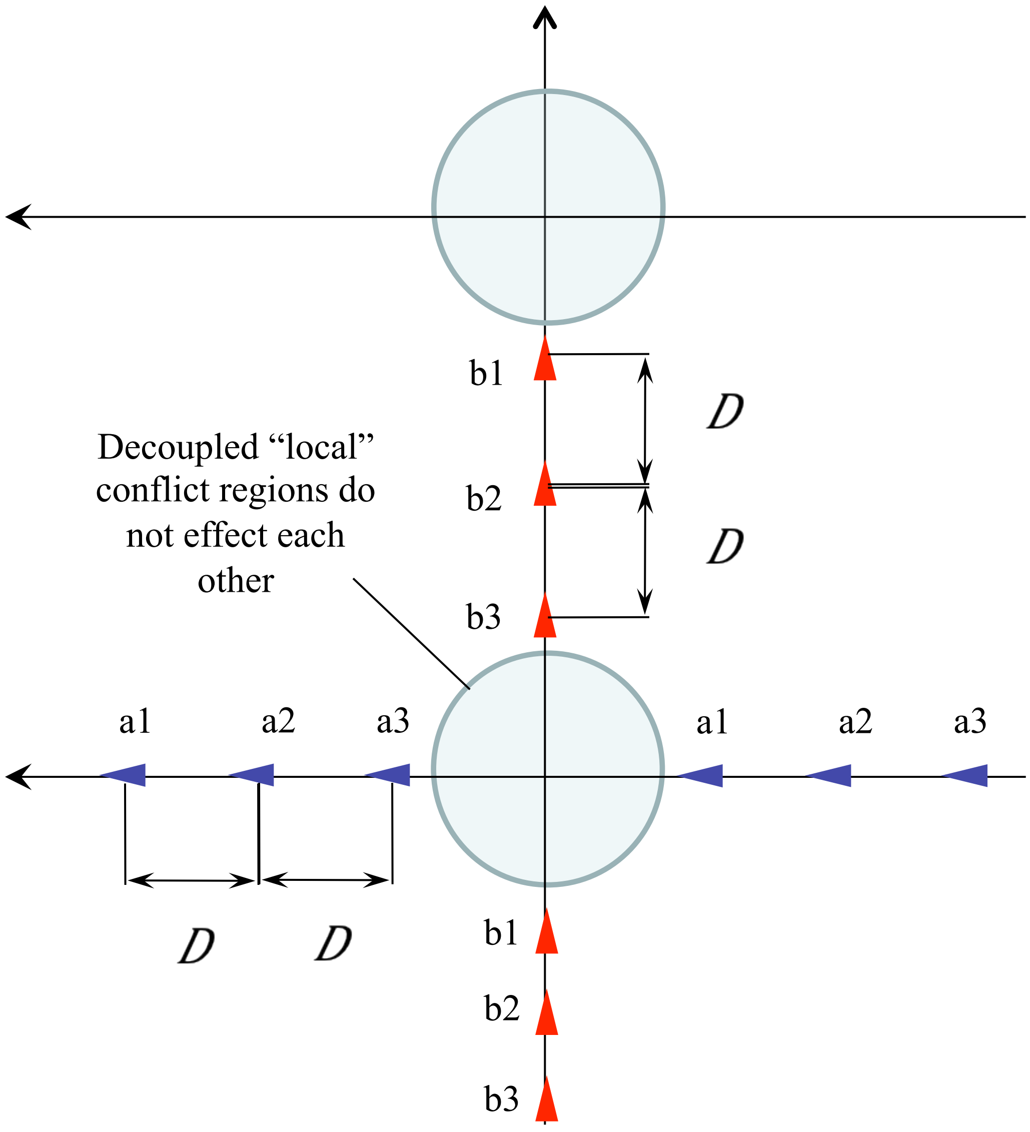
- All resolution is done within local zone
- After passing zone aircrafts return to original destined route
- Solving one conflict does not lead to a new conflict outside
- Therefore no domino effects, provided the the CRP areas are disjoint (sufficiently sparse intersections)

Solution to Issue 2- Decentralized



- After 1st CRP; aircraft are back on route and in same sequence.
- 1st CRP does not affect the next CRP
- Local in space and time → **decentralized**

Solution to Issue 3- Local Stability → global stability



- No new conflicts
- Finite number of conflicts
- Each CRP bounded in space and time
- Therefore, can guarantee **globally stable if locally stable**

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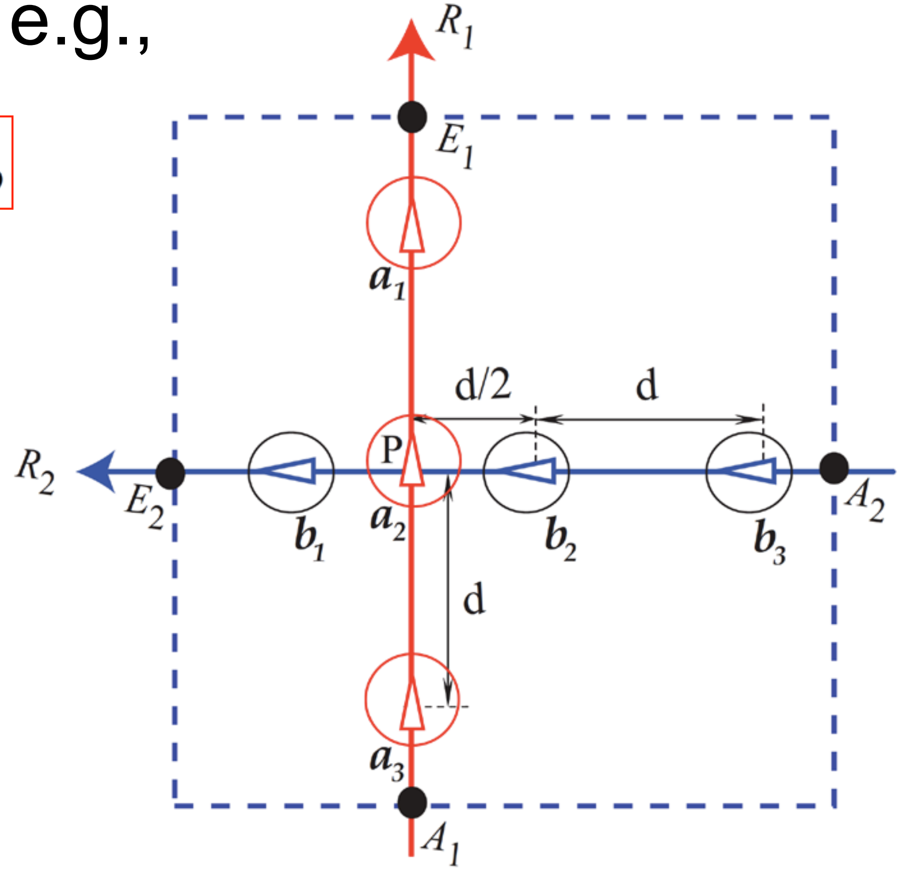
Basic Idea of CRP

Two flows can intersect if there is sufficient spacing between aircraft. The min spacing depends on angle of intersection, e.g.,

$$d_{\pi/2} = 2\sqrt{2}d_{sep}$$

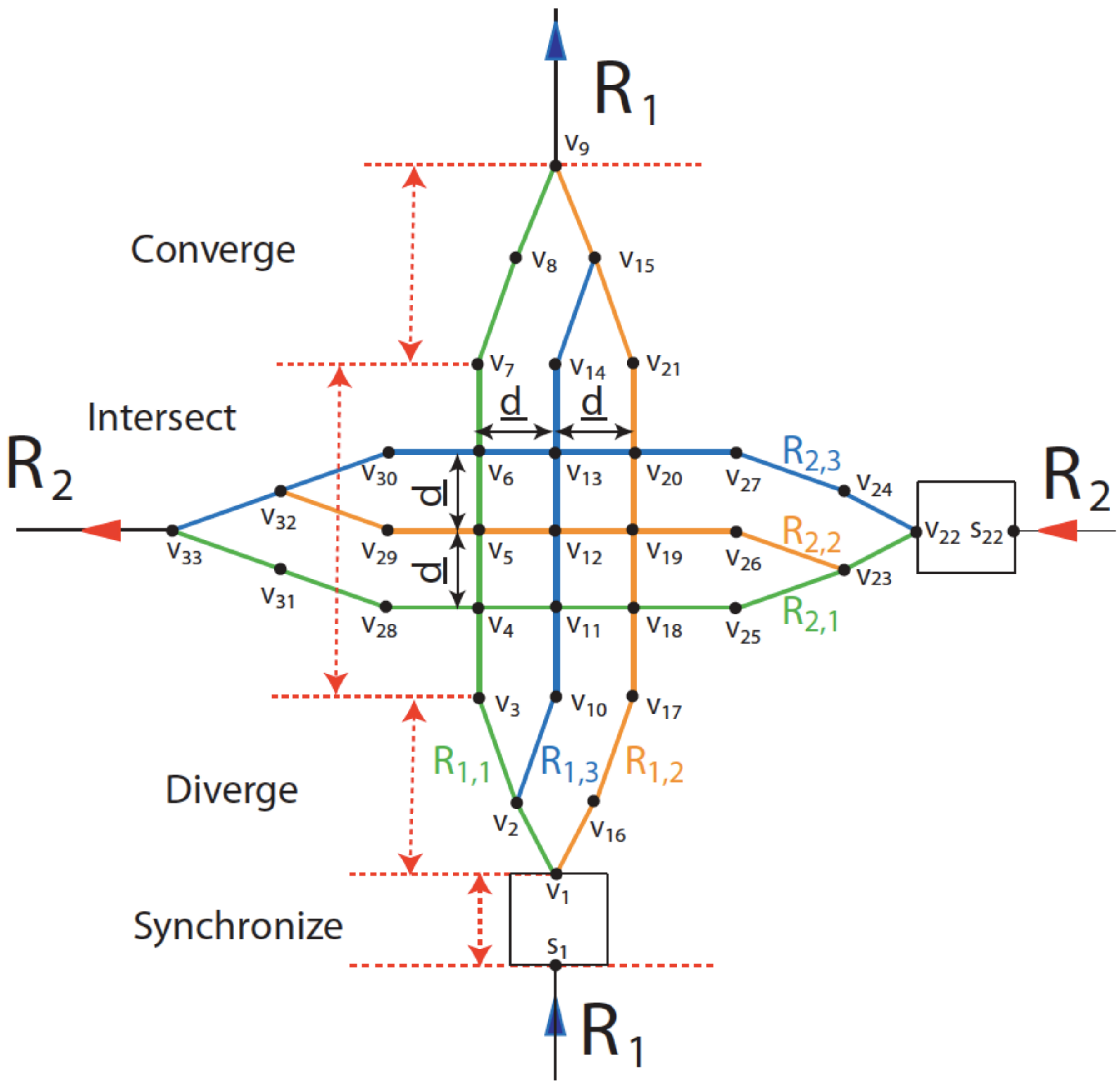


What if there is insufficient spacing?

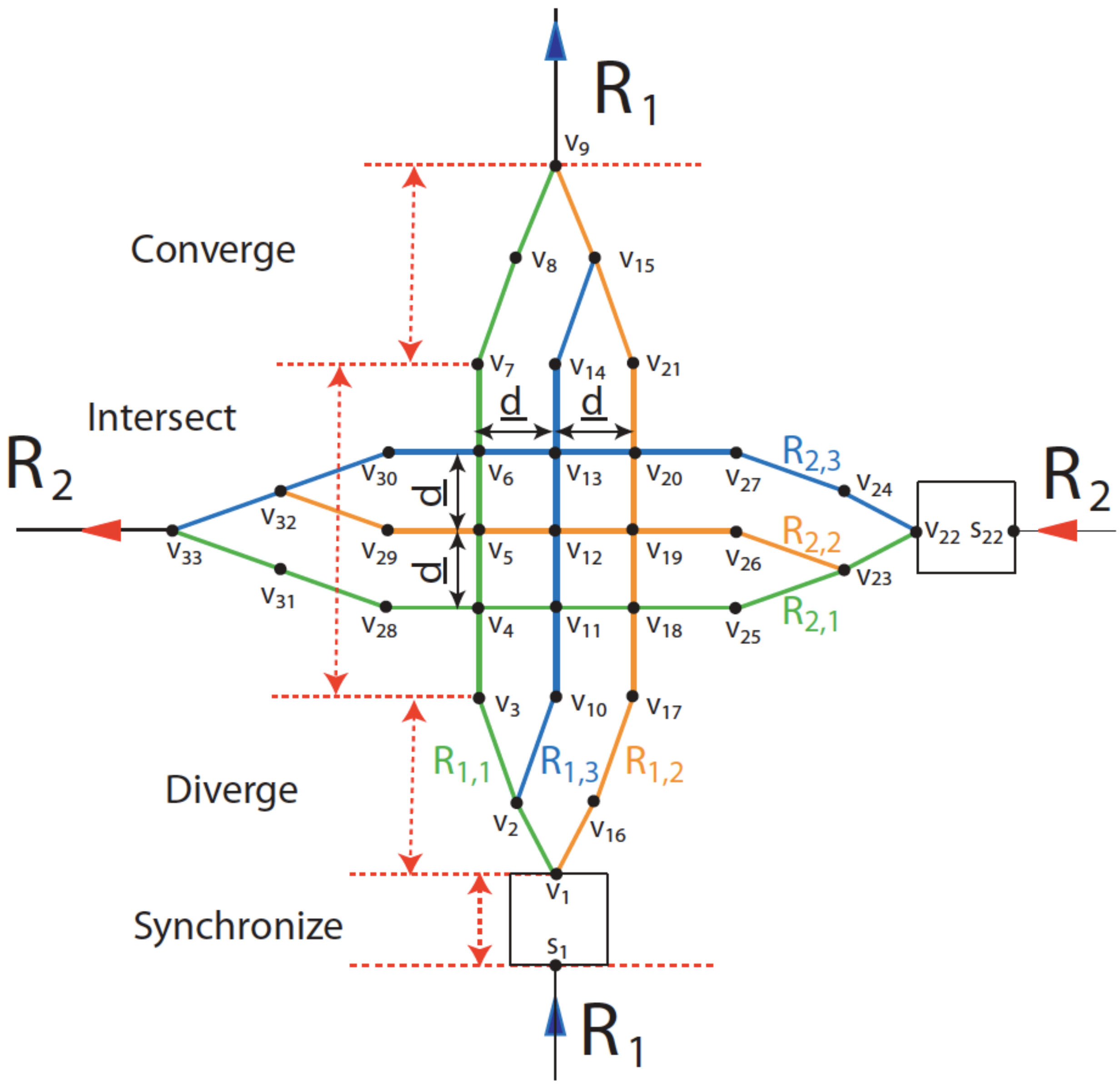
What if there is insufficient spacing?

- Then separate the flow into multiple paths and then intersect

3-way split for 90° intersections



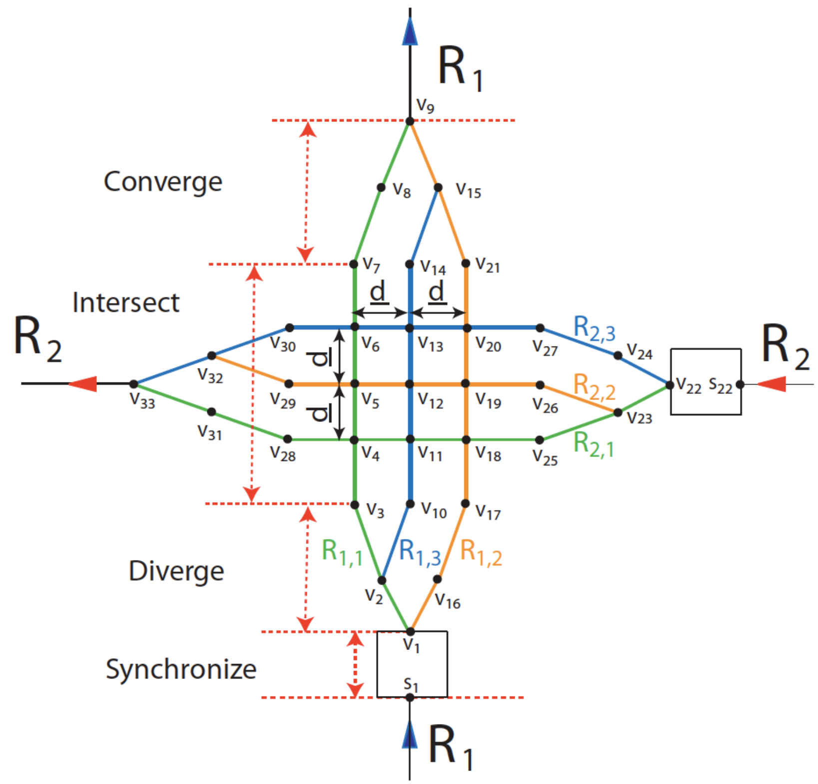
Critical Aspect --- use equal length paths



Critical Aspects (1) use equal length paths

Ensures

1) Sequence is maintained
2) Separation is maintained

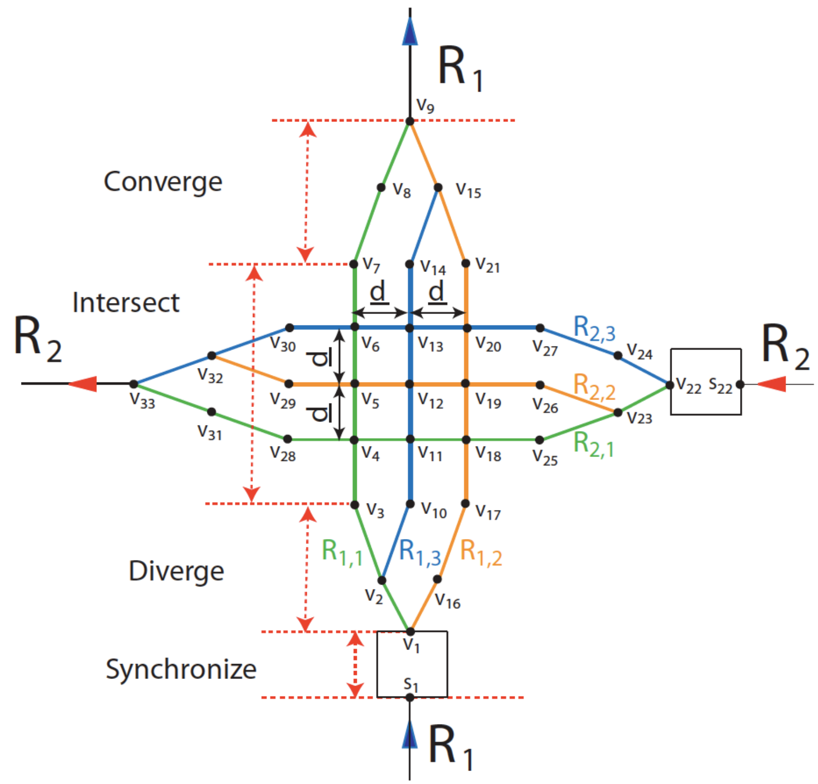


Critical Aspects (1) use equal length paths
(2) return to original routes

Ensures

1) Sequence is maintained
2) Separation is maintained

3) No additional conflicts outside local CRP



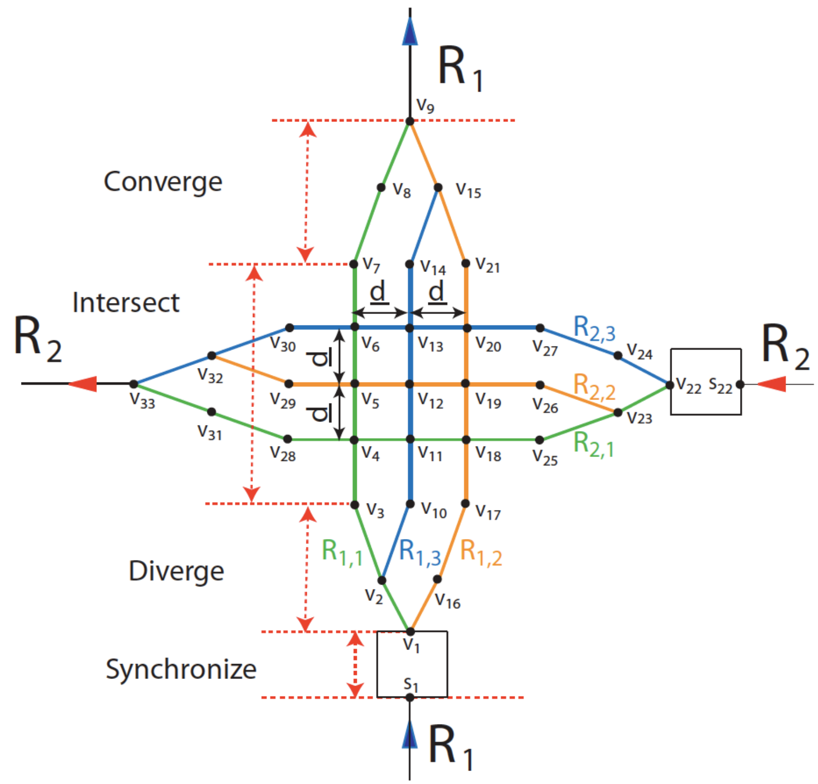
Critical Aspects (1) use equal length paths; (2) return to original routes; **(3) synchronize**

Ensures

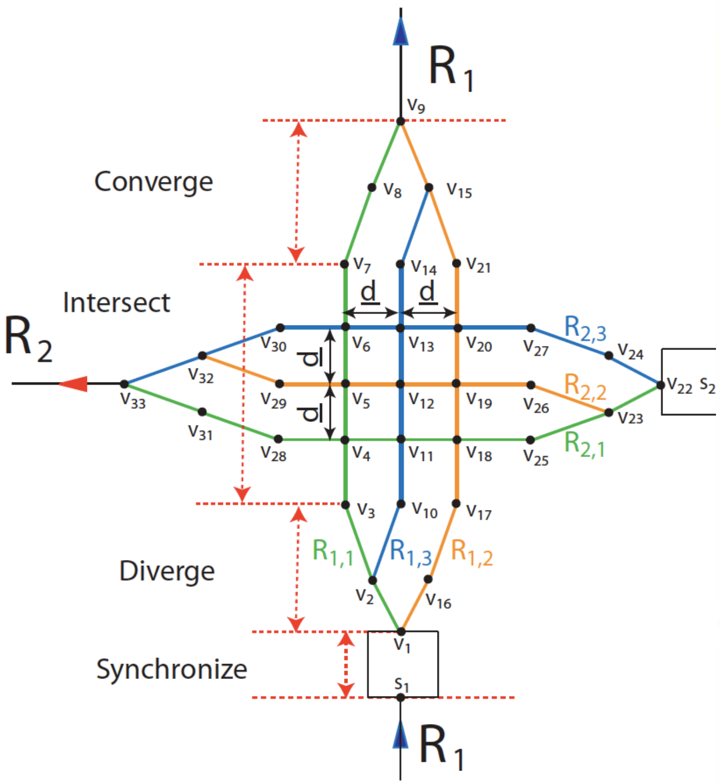
1) Sequence is maintained
2) Separation is maintained

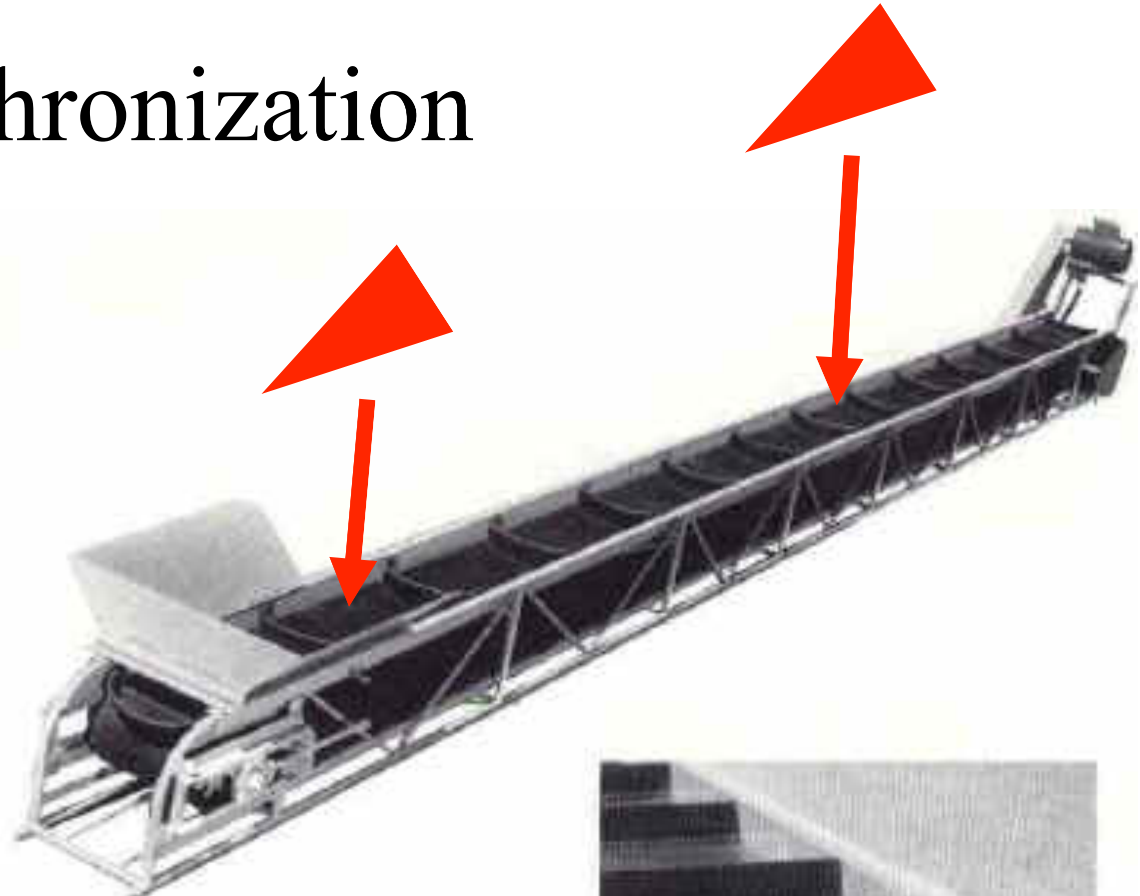
3) No additional conflicts outside local CRP

4) Intersecting flows should be centered before intersections



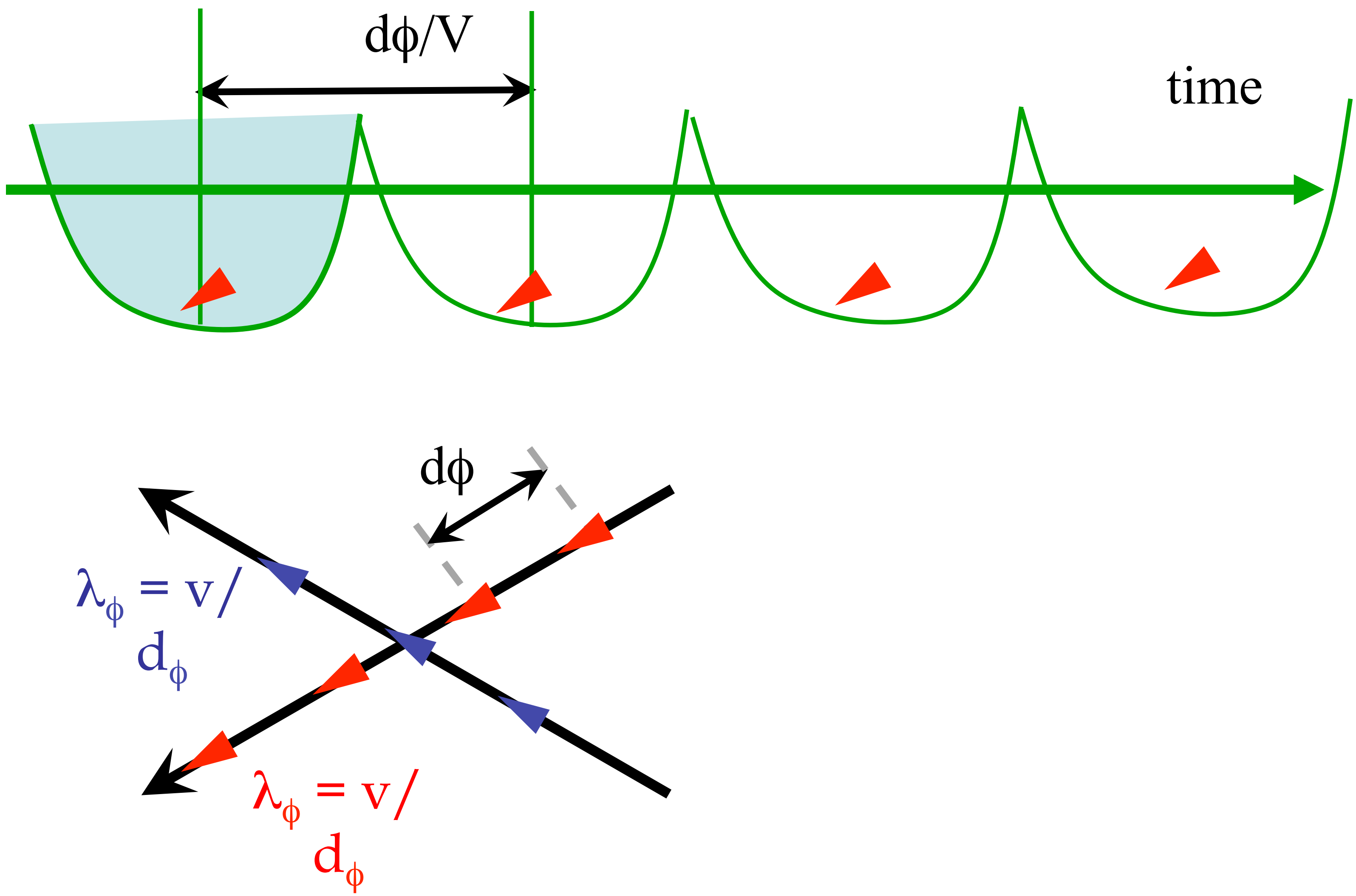
Synchronization



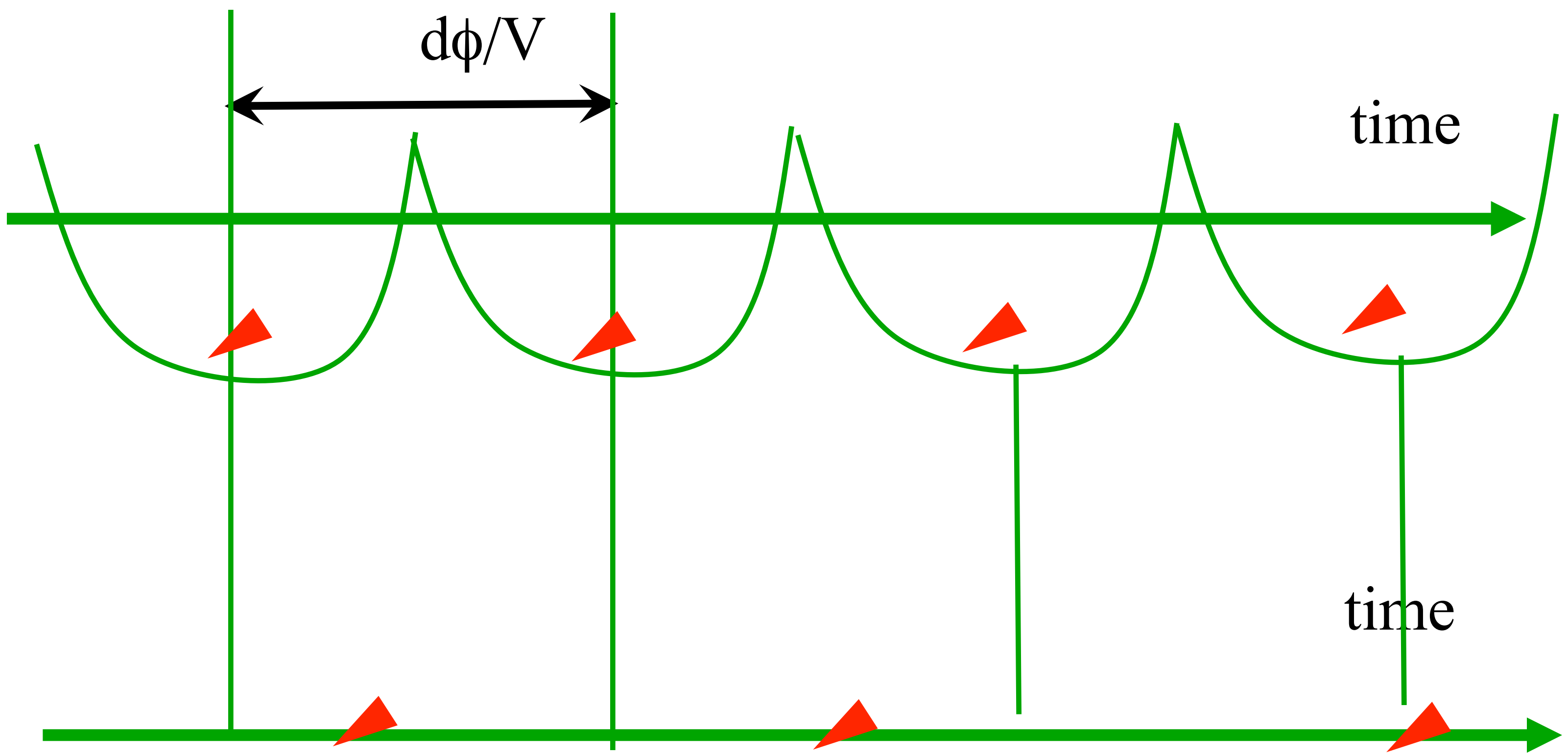


Buckets in time

Dimension of buckets

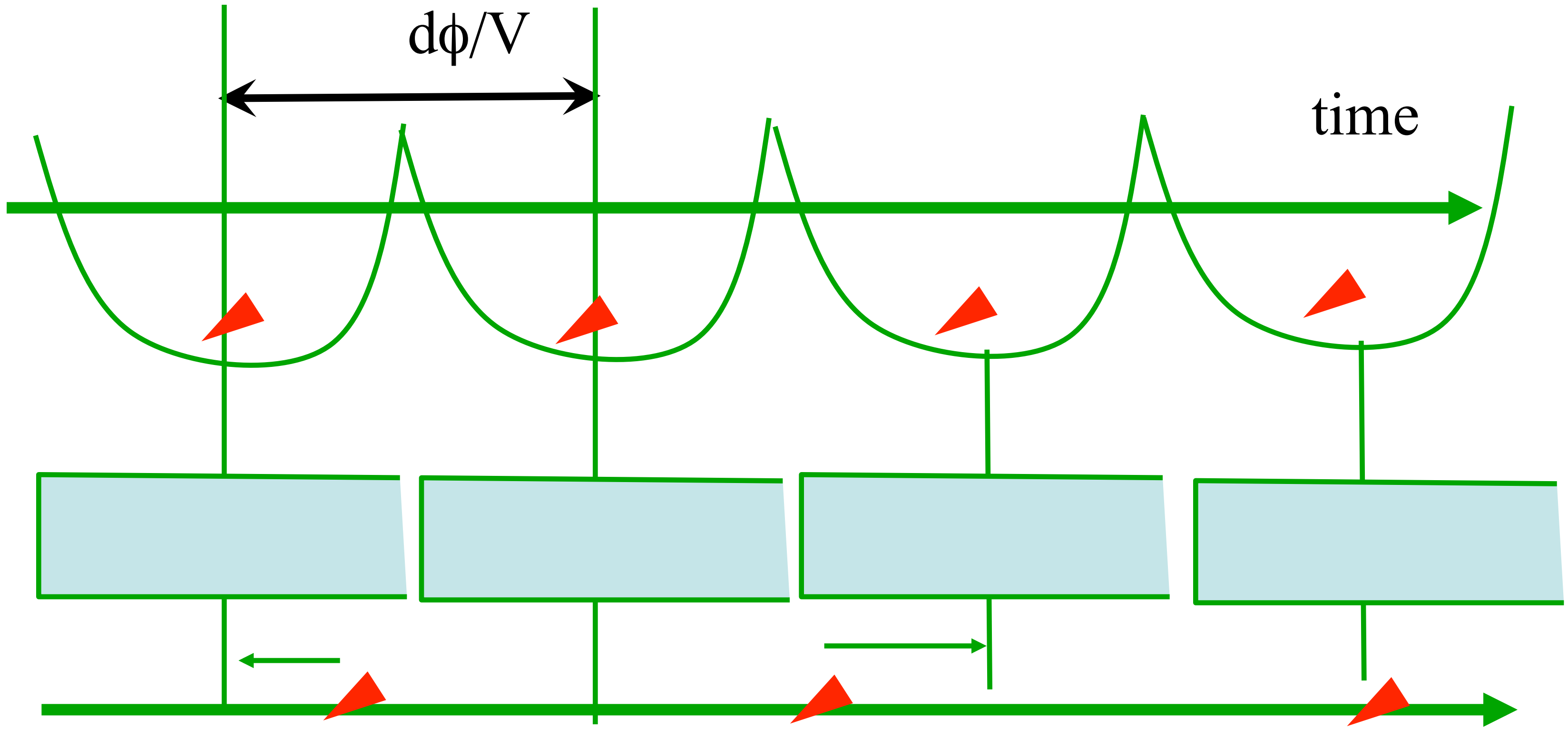


Aircraft Separated but not synchronized

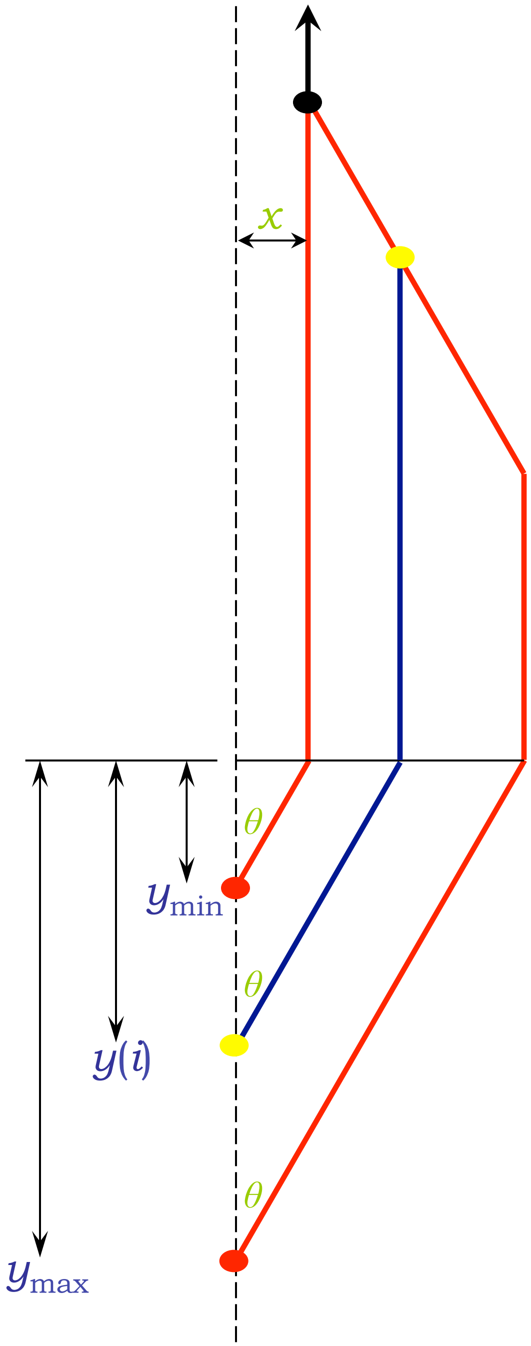


However aircraft is minimally spaced at center the bucket width!
Therefore no more than one in any bucket!

Actual aircraft is not synchornized



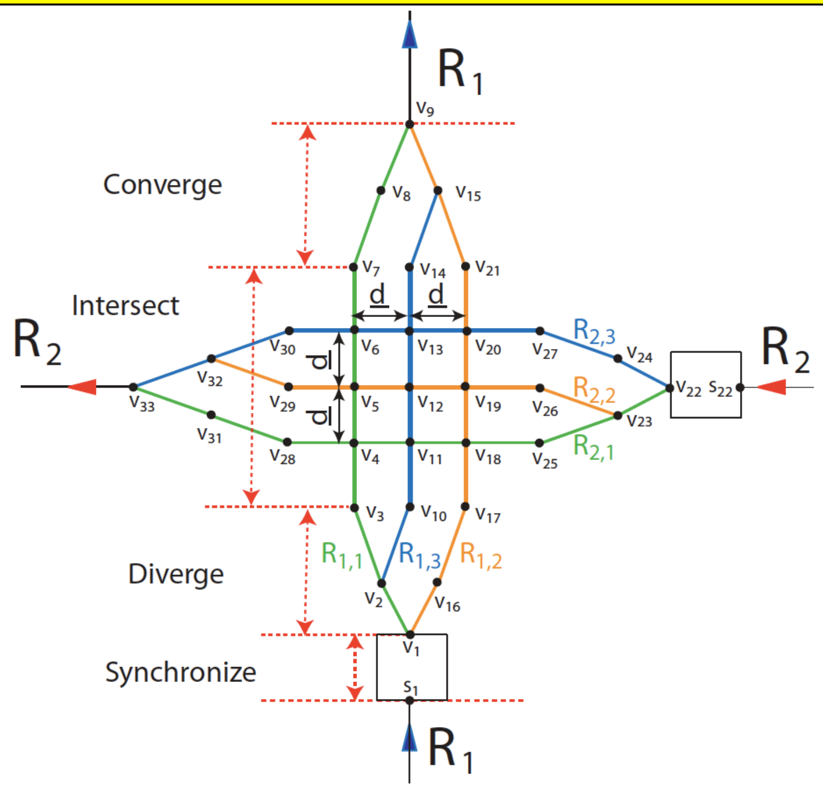
Need to adjust for the possible offsets in arrival

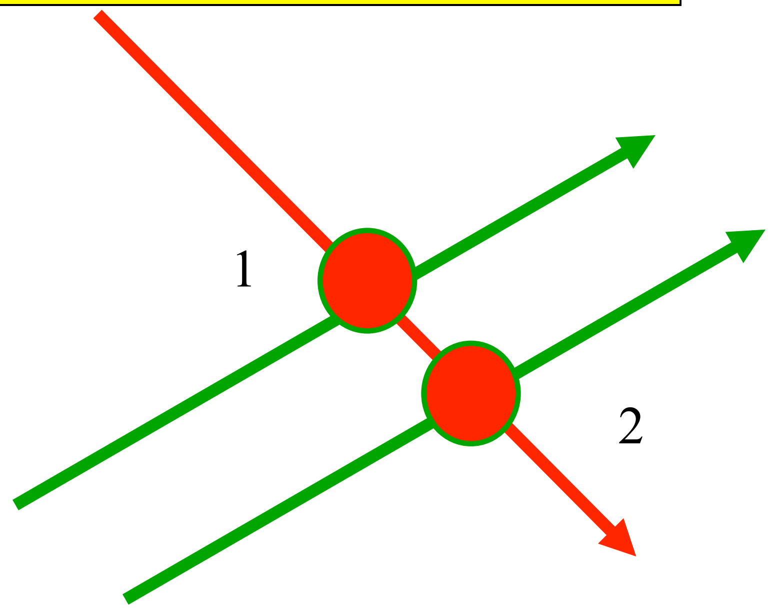


Synchronization using path extension

Standard process near airports
(Alternative to increasing speed)

Recap of CRP





a) Exit has same order, spacing and sequence as entry
b) Enables CRP at different conflict regions (1 and 2) to be decoupled.
c) A decentralized process which guarantees global stability
d) Enables the use of re-routing procedures without need to merge

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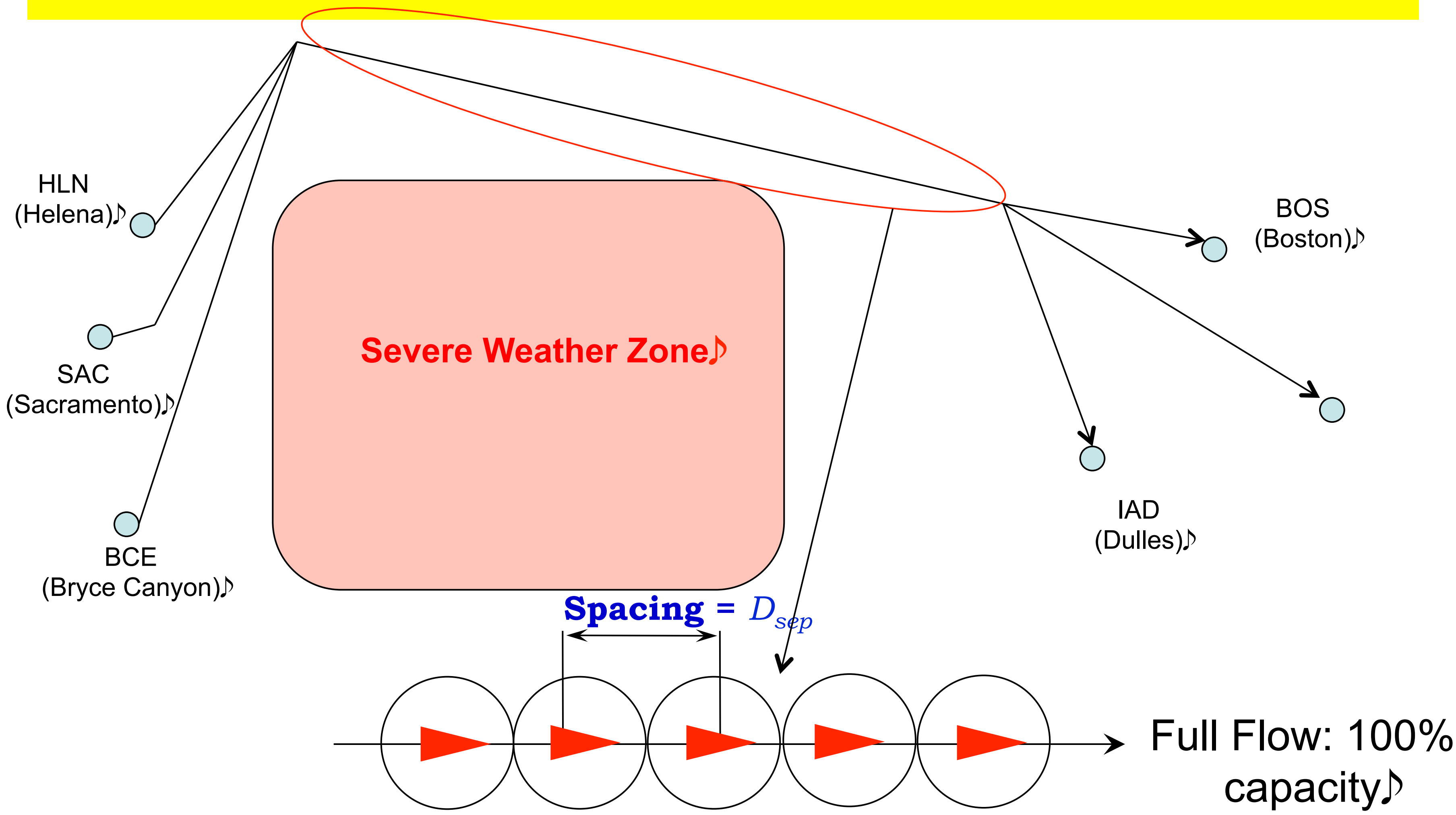
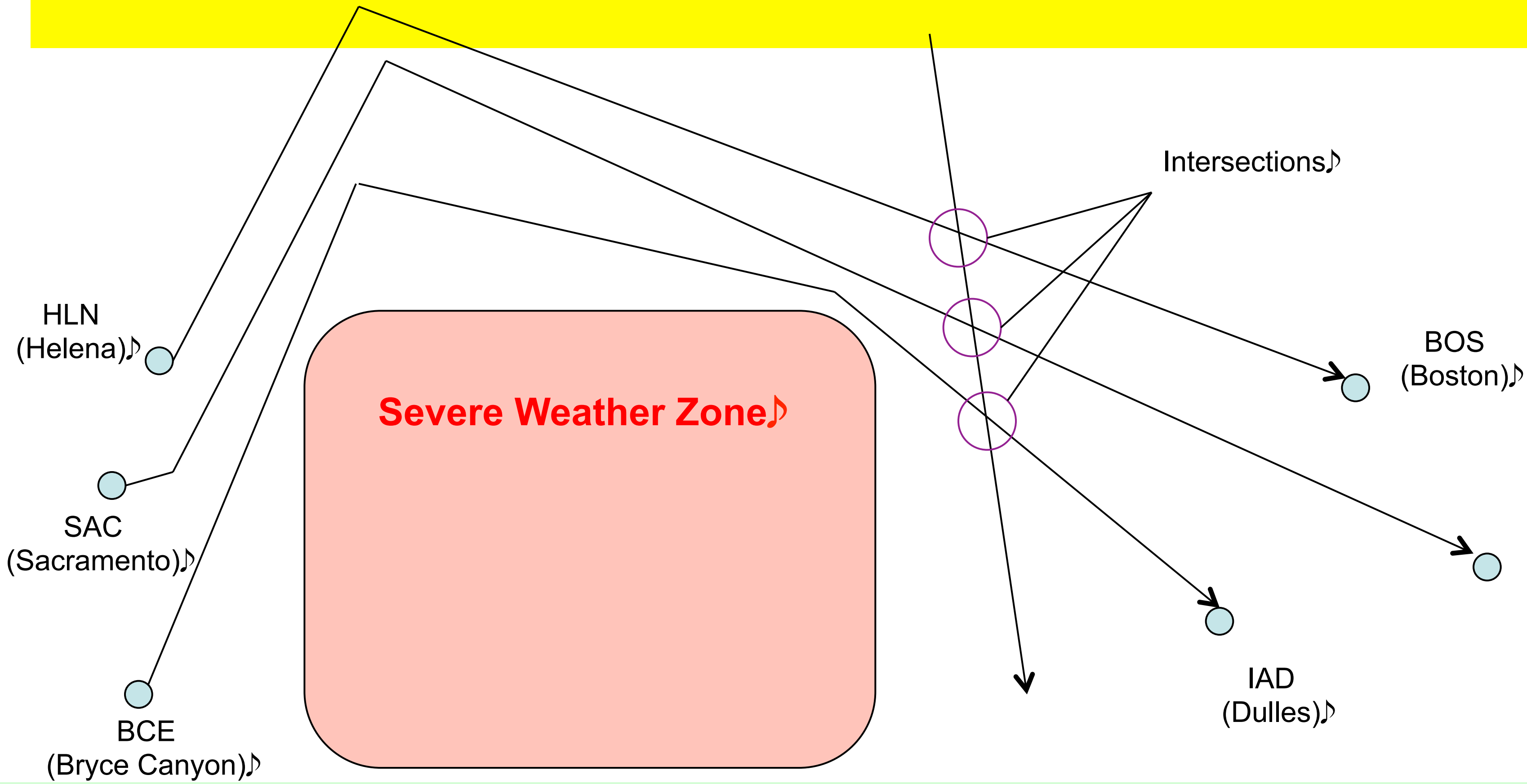
Conclusion 1/3



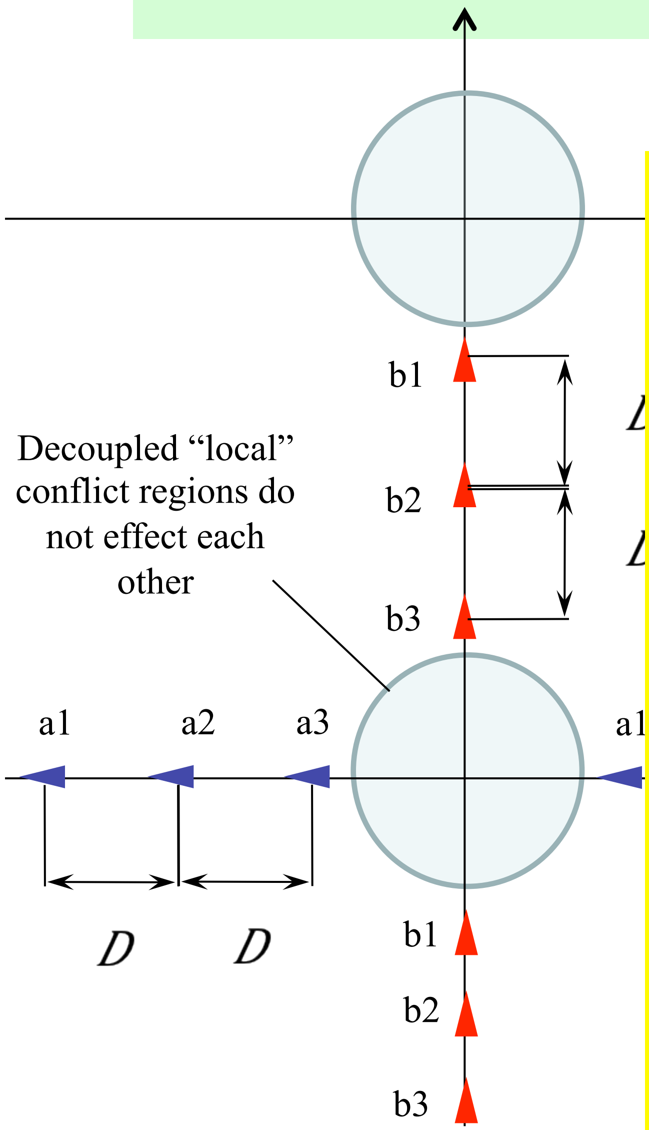
- Main rerouting problem: Capacity loss due to merging

Conclusion 2/3



- Alternative with no merges (loss of simplicity)
- To enable, we need en-route (potentially automated) CRP that avoids domino effect, is decentralized & guarantees stability

Conclusion 3/3



- Proposed solution CRP solves these issues with local decoupled CRPs
- **Main ideas;**

  1) **split paths** --- increase spacing at intersection

  2) **equal length** paths --- maintains sequence and spacing for decoupling CRPs (decentralized)

  3) **merge back** --- no new conflicts, i.e., avoid domino effects