Spatial Indexing

ΠΜΣ "Ερευνητικές Κατευθύνσεις στην Πληροφορική"

Επεξεργασία και Ανάλυση Δεδομένων

SPRING SEMESTER 2020

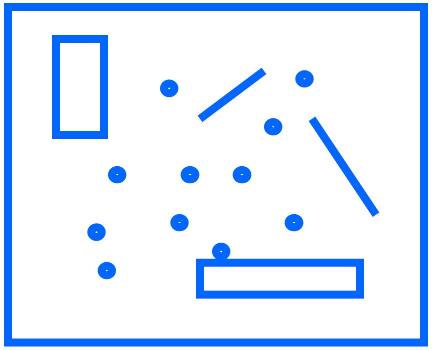
Material taken from 15-415 - Database Applications class @Carnegie Mellon
C. Faloutsos

SAMs - Detailed outline

- spatial access methods
  - problem dfn
  - z-ordering
  - R-trees

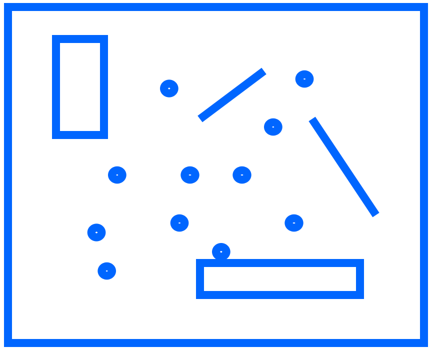
Spatial Access Methods - problem

- Given a collection of geometric objects (points, lines, polygons, ...)
- organize them on disk, to answer spatial queries (like??)



Spatial Access Methods - problem

- Given a collection of geometric objects (points, lines, polygons, ...)
- organize them on disk, to answer
  - point queries
  - range queries
  - k-nn queries
  - spatial joins (‘all pairs’ queries)



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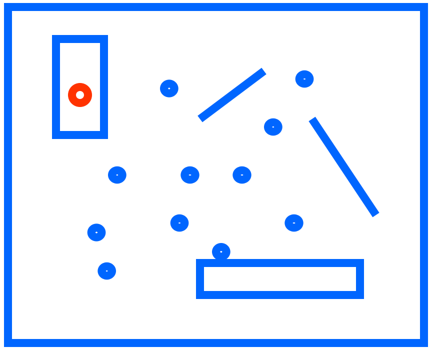

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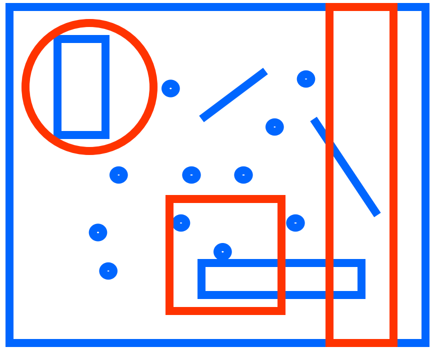

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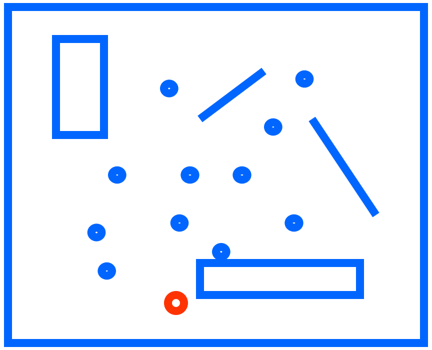
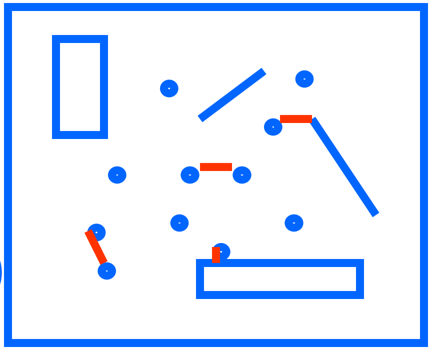


Spatial Access Methods - problem

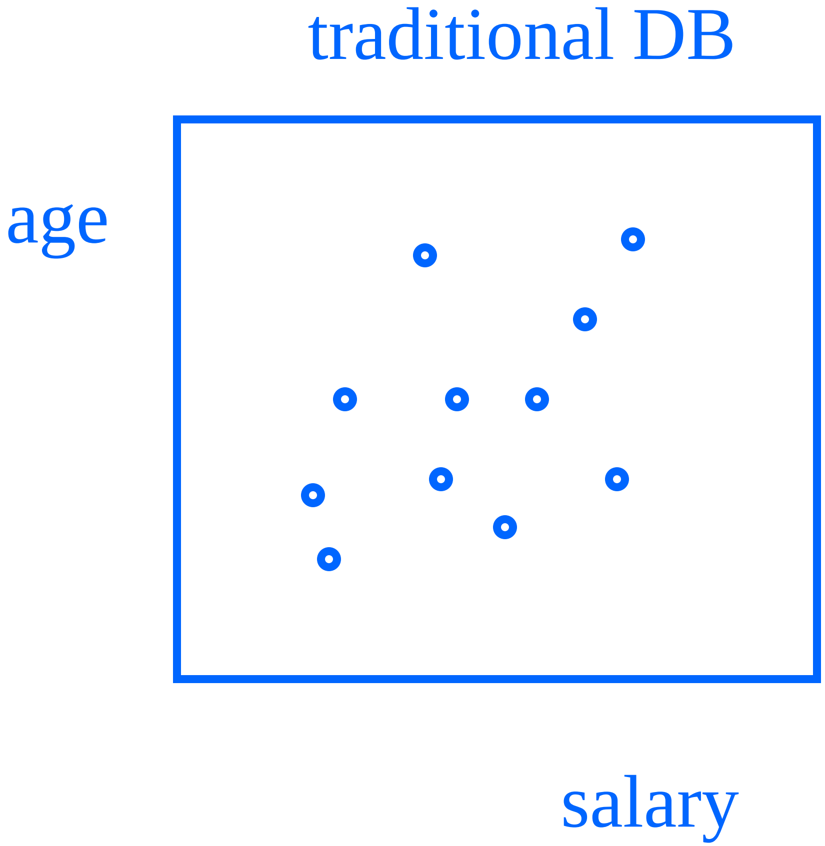
- Given a collection of geometric objects (points, lines, polygons, ...)
- organize them on disk, to answer
  - point queries
  - range queries
  - k-nn queries
  - spatial joins ('all pairs' within ε)

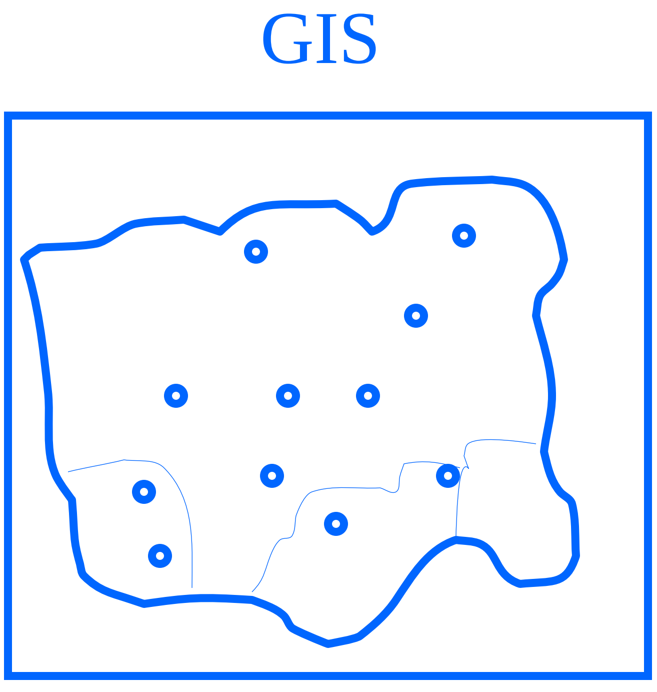


SAMs - motivation

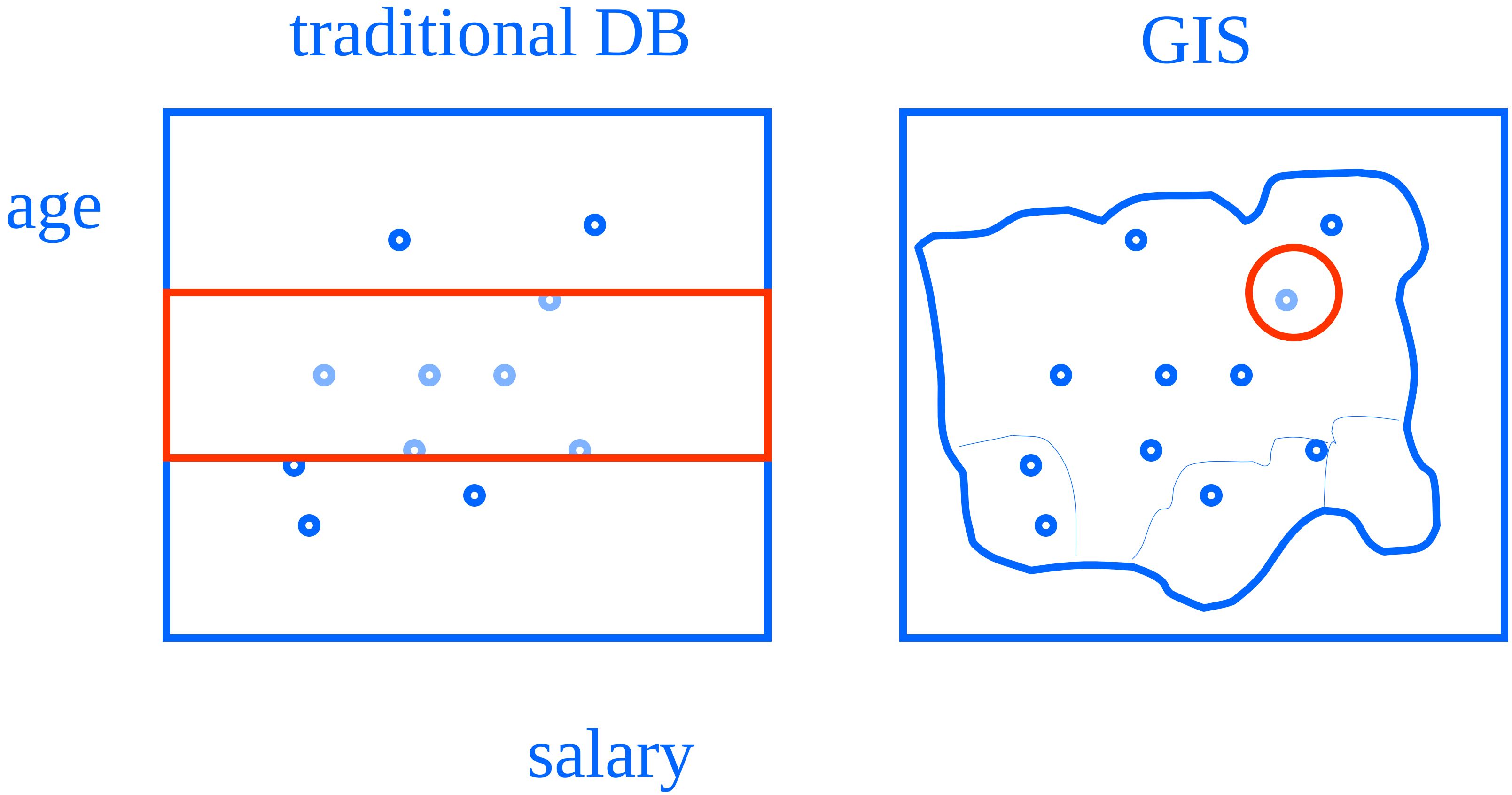
- Q: applications?

SAMs - motivation



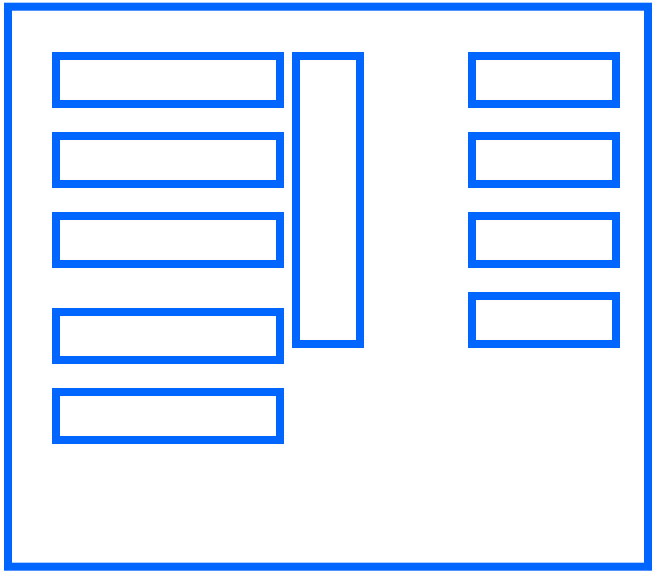


SAMs - motivation



SAMs - motivation

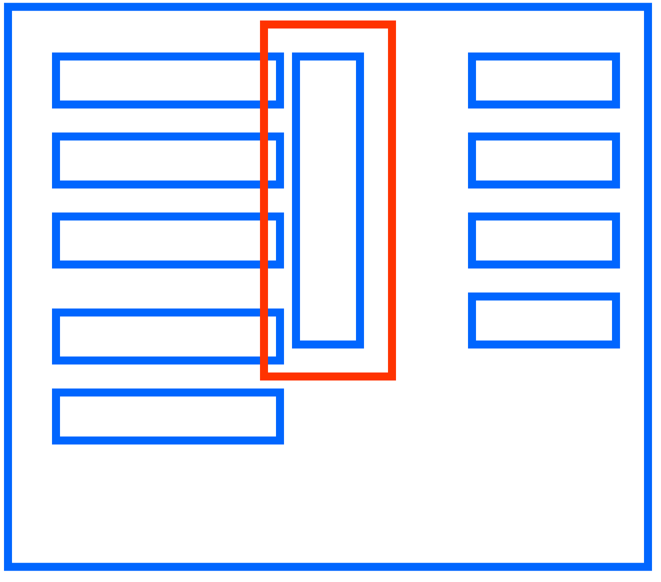
CAD/CAM



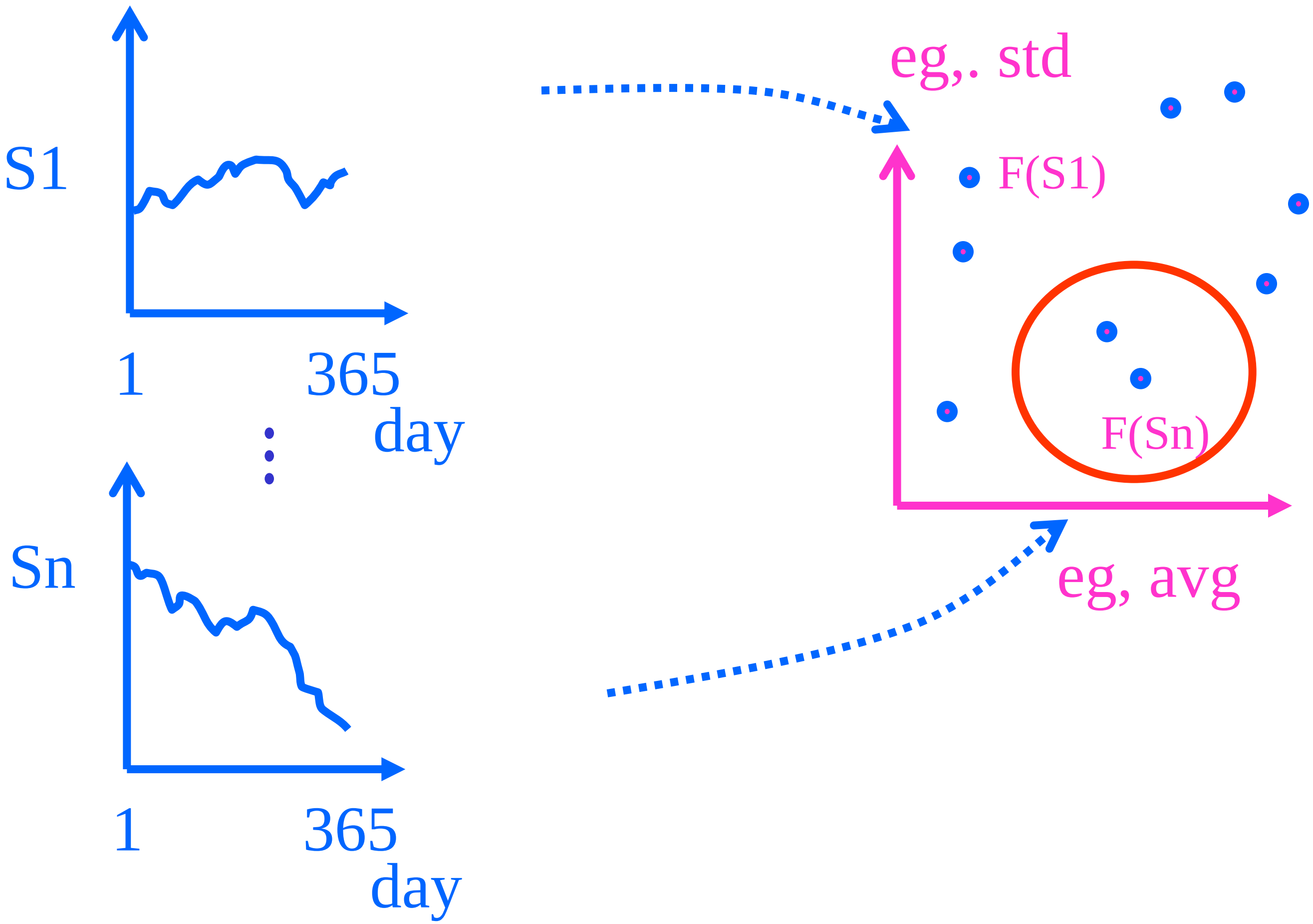
find elements
too close
to each other

SAMs - motivation

CAD/CAM



SAMs - motivation



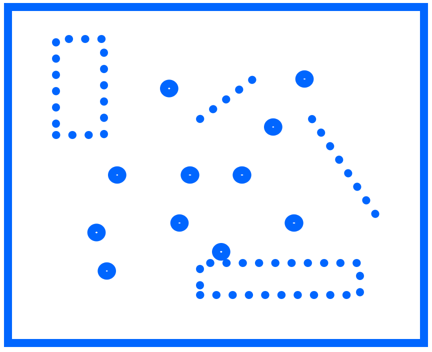
SAMs - Detailed outline

- spatial access methods
  - problem dfn
  - z-ordering
  - R-trees

SAMs: solutions

- z-ordering
- R-trees
- (grid files)

Q: how would you organize, e.g., *n*-dim points, on disk? (*C* points per disk page)



z-ordering

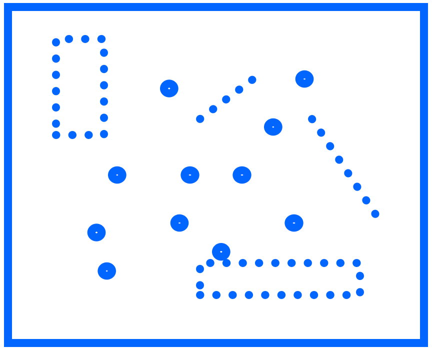
Q: how would you organize, e.g., *n*-dim points, on disk? (*C* points per disk page)

Hint: reduce the problem to 1-d points(!!)

Q1: why?

A:

Q2: how?



z-ordering

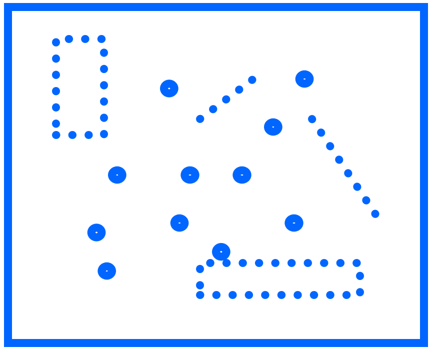
Q: how would you organize, e.g., *n*-dim points, on disk? (*C* points per disk page)

Hint: reduce the problem to 1-d points (!!)

Q1: why?

A: B-trees!

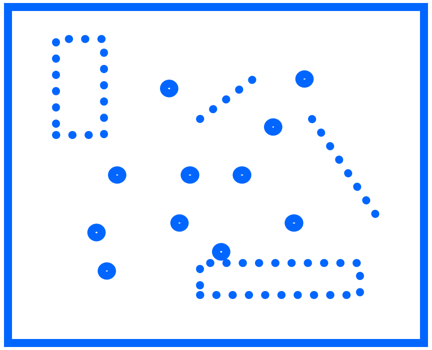
Q2: how?



z-ordering

Q2: how?

A: assume finite granularity; z-ordering = bit-shuffling = N-trees = Morton keys = geo-coding = ...

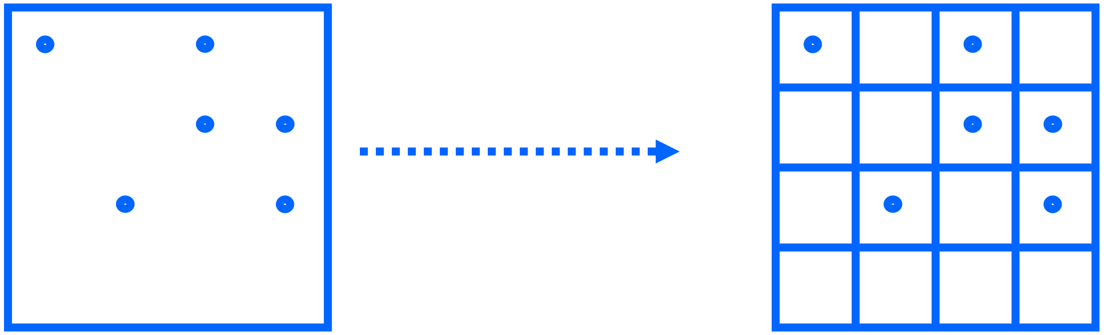


z-ordering

Q2: how?

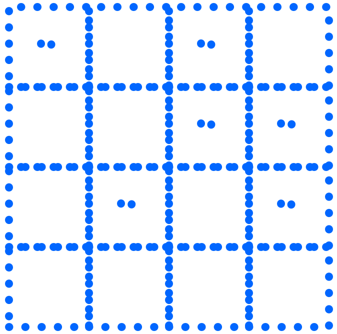
A: assume finite granularity (e.g., 2^{32}x2^{32} ; 4x4 here)

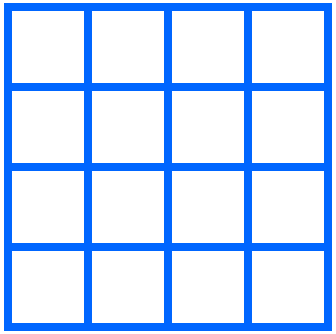
Q2.1: how to map n-d cells to 1-d cells?



z-ordering

Q2.1: how to map *n*-d cells to 1-d cells?



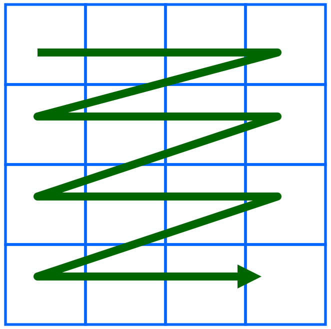


z-ordering

Q2.1: how to map *n*-d cells to 1-d cells?

A: row-wise

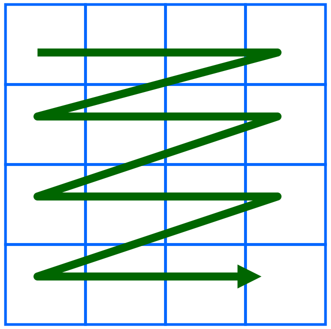
Q: is it good?



z-ordering

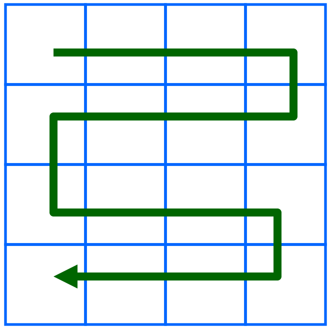
Q: is it good?

A: great for ‘x’ axis; bad for ‘y’ axis



z-ordering

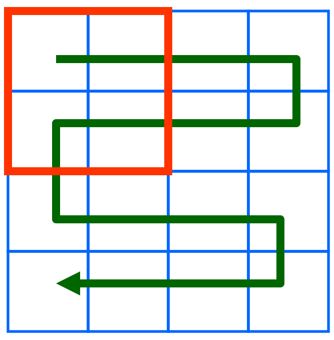
Q: How about the ‘snake’ curve?

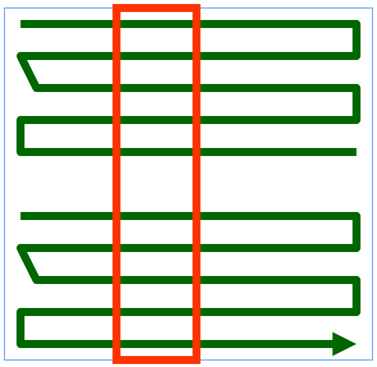


z-ordering

Q: How about the ‘snake’ curve?

A: still problems:





2^32

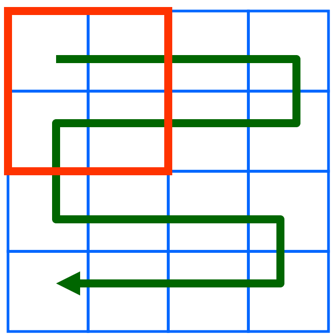
2^32

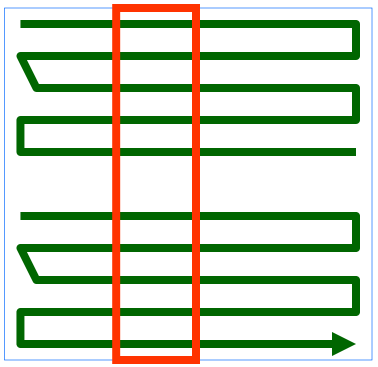
z-ordering

Q: Why are those curves ‘bad’?

A: no distance preservation (~ clustering)

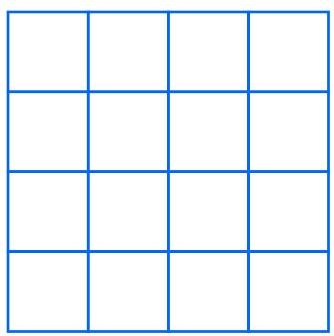
Q: solution?





z-ordering

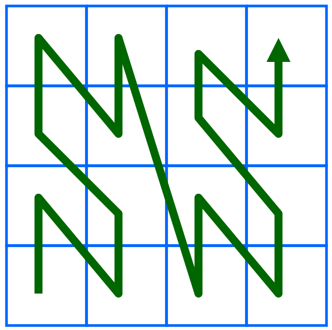
Q: solution? (w/ good clustering, and easy to compute, for 2-d and *n*-d?)



z-ordering

Q: solution? (w/ good clustering, and easy to compute, for 2-d and *n*-d?)

A: z-ordering/bit-shuffling/linear-quadtrees



'looks' better:

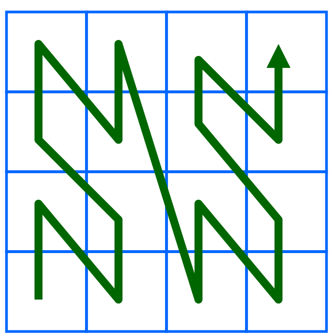
- few long jumps;
- scoops out the whole quadrant before leaving it
- a.k.a. space filling curves

z-ordering

z-ordering/bit-shuffling/linear-quadtrees

Q: How to generate this curve ($z = f(x,y)$)?

A: 3 (equivalent) answers!

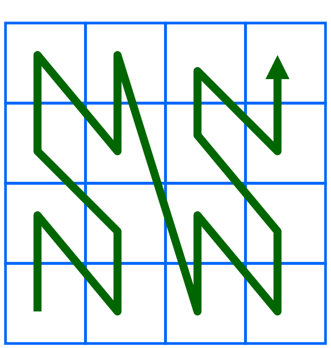


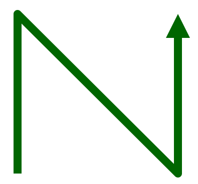
z-ordering

z-ordering/bit-shuffling/linear-quadtrees

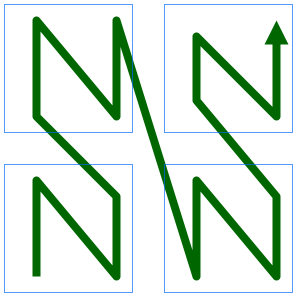
Q: How to generate this curve ($z = f(x,y)$)?

A1: ‘z’ (or ‘N’) shapes, RECURSIVELY



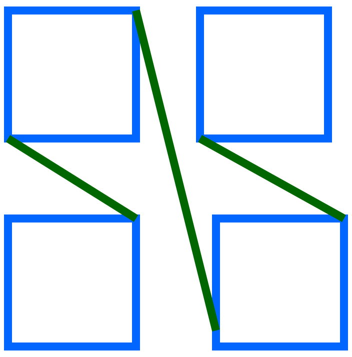


order-1



order-2

...

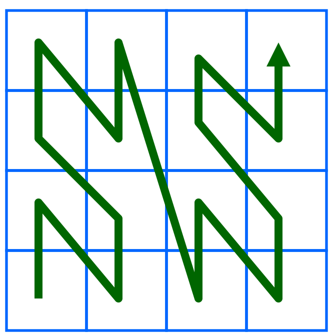


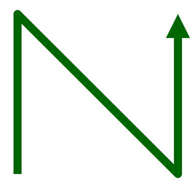
order (n+1)

z-ordering

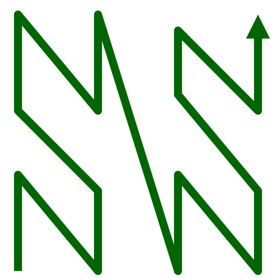
Notice:

- self similar (we'll see about fractals, soon)
- method is hard to use: $z =? f(x,y)$



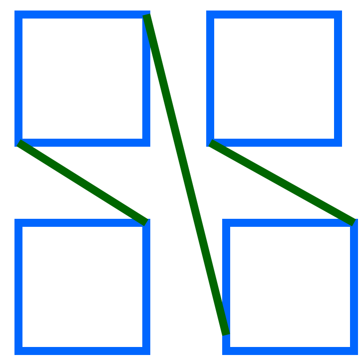


order-1



order-2

…



order (n+1)

z-ordering

z-ordering/**bit-shuffling**/linear-quadtrees

Q: How to generate this curve ($z = f(x,y)$)?

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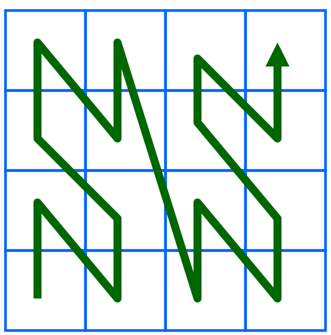
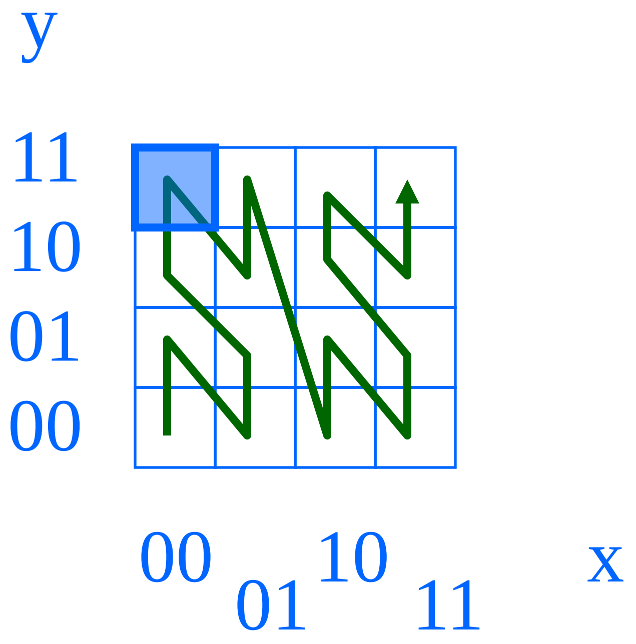
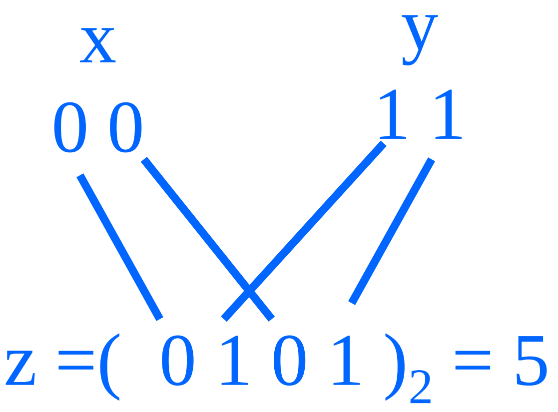


Method #2?

z-ordering

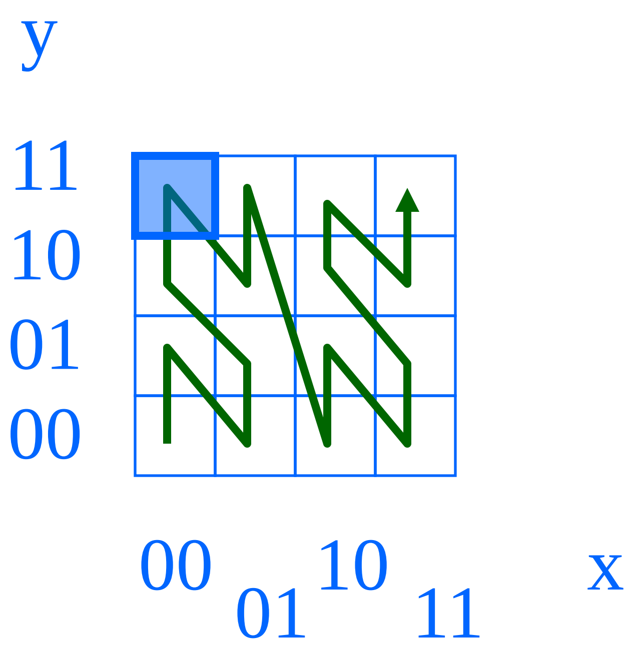
bit-shuffling

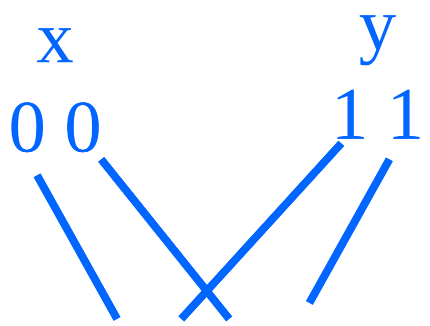




z-ordering

bit-shuffling





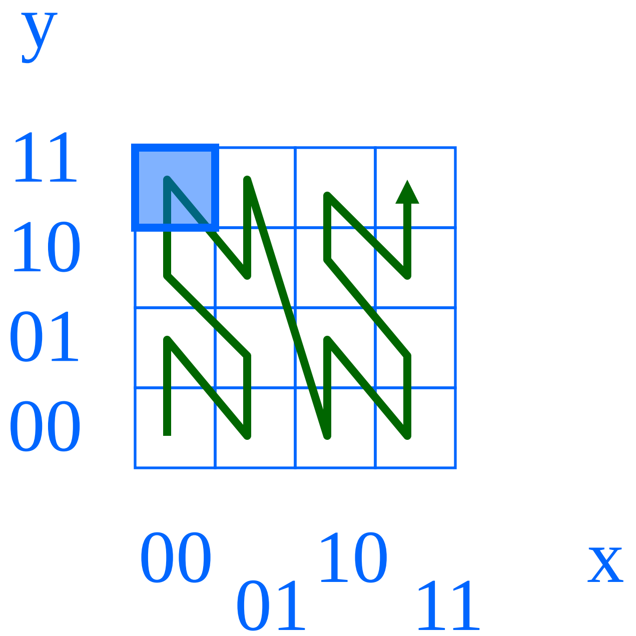
$z = (\ 0\ 1\ 0\ 1\ )_2 = 5$

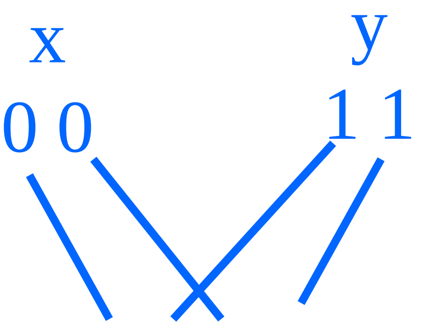
How about the reverse:

$(x,y) = g(z)$?

z-ordering

bit-shuffling





$z = (\ 0\ 1\ 0\ 1\ )_2 = 5$

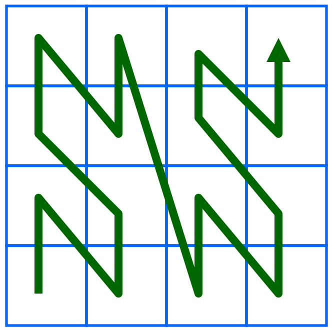
How about *n*-d spaces?

z-ordering

z-ordering/bit-shuffling/**linear-quadtrees**

Q: How to generate this curve ($z = f(x,y)$)?

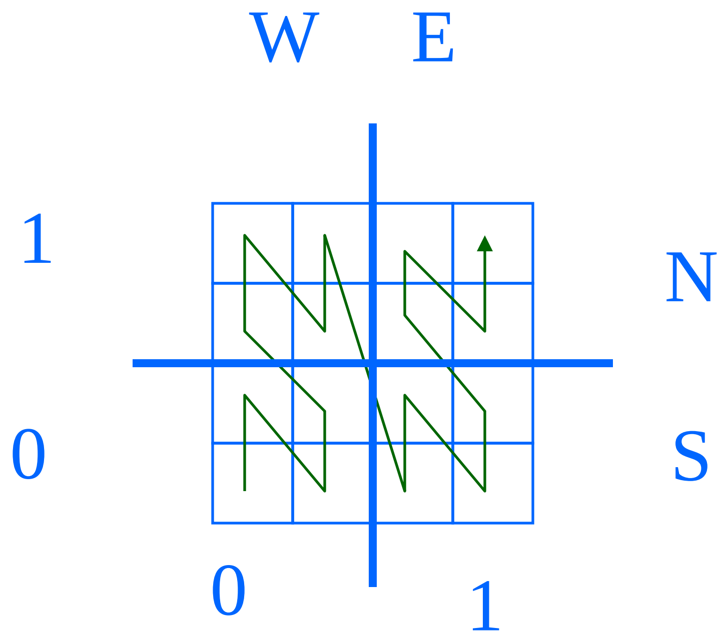
A: 3 (equivalent) answers!

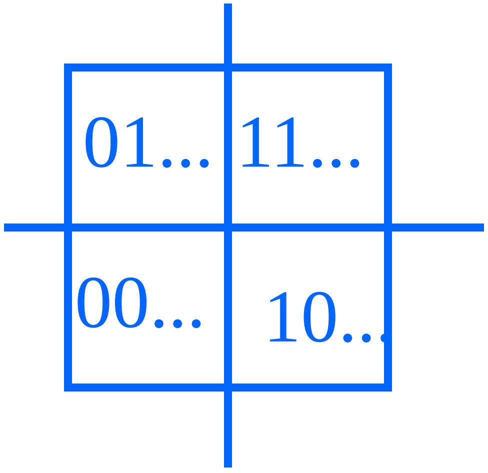


Method #3?

z-ordering

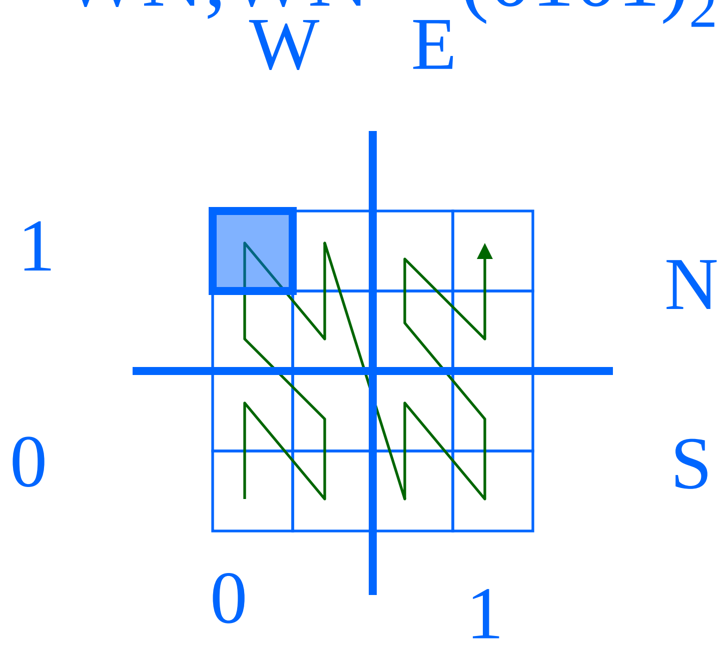
linear-quadtrees : assign N->1, S->0 e.t.c.

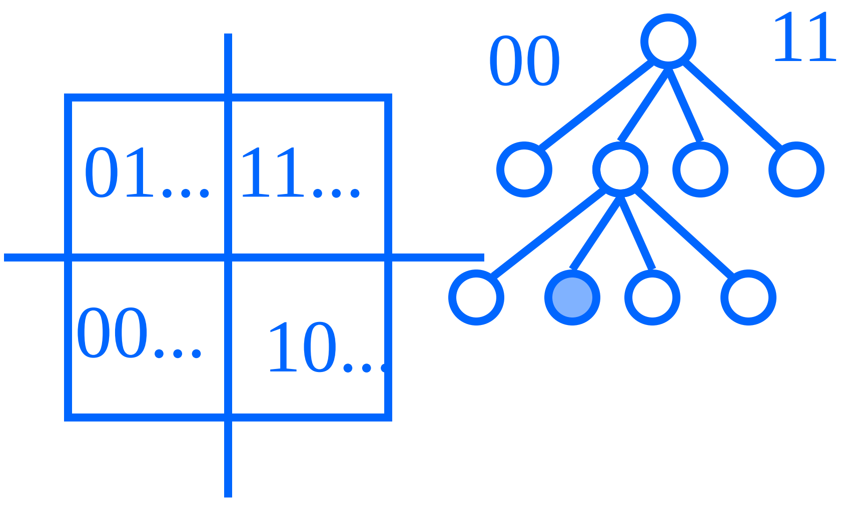




z-ordering

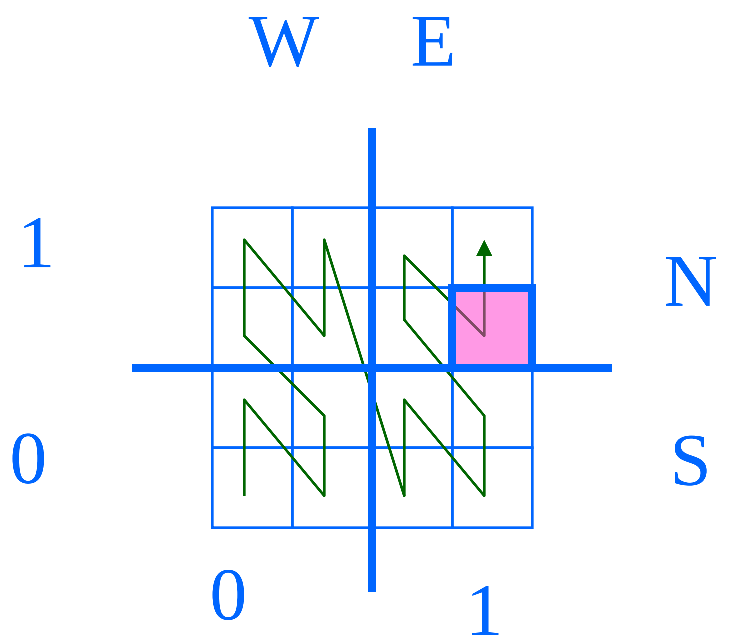
... and repeat recursively. Eg.: $z_{blue\text{-}cell}$ = WN;WN = $(0101)_2$ = 5





z-ordering

Drill: z-value of magenta cell, with the three methods?



z-ordering

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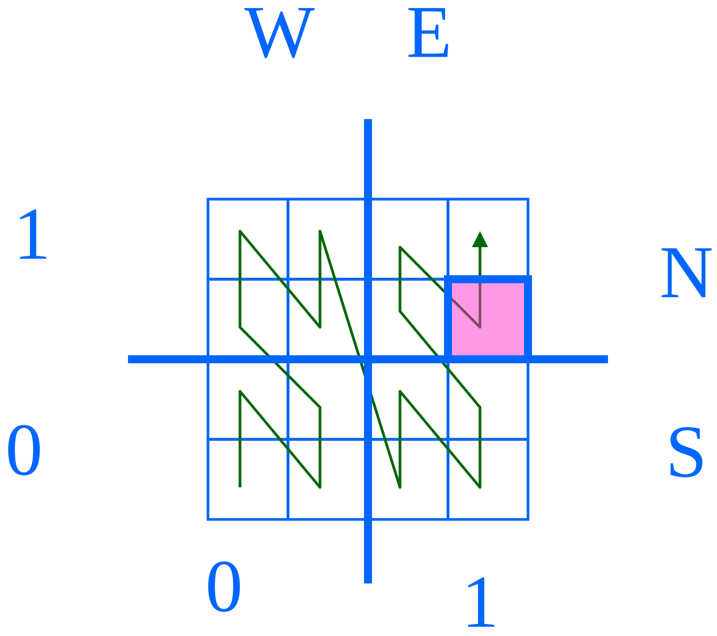
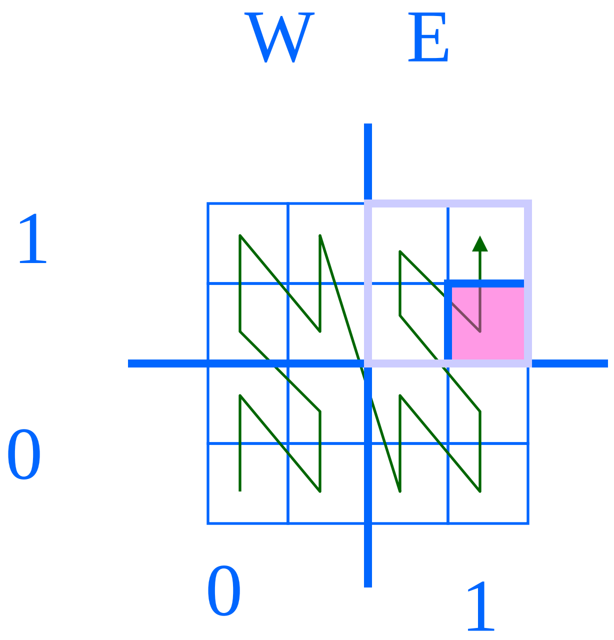


method#1: 14

method#2: shuffle(11;10)= $(1110)_2$ = 14

z-ordering

Drill: z-value of magenta cell, with the three methods?



method#1: 14

method#2: shuffle(11;10)= $(1110)_2$ = 14

method#3: EN;ES = ... = 14

z-ordering - Detailed outline

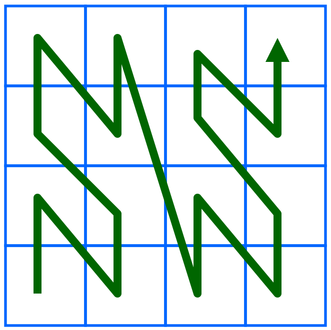
- spatial access methods
  - z-ordering
    - main idea - 3 methods
    - use w/ B-trees; algorithms (range, knn queries ...)
    - non-point (eg., region) data
    - analysis; variations
  - R-trees

z-ordering - usage & algo’s

Q1: How to store on disk?

A:

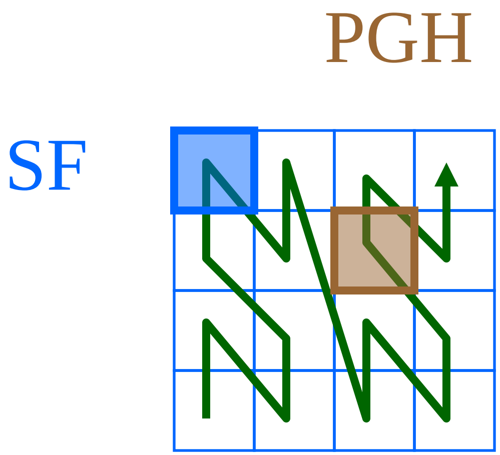
Q2: How to answer range queries etc



z-ordering - usage & algo's

Q1: How to store on disk?

A: treat z-value as primary key; feed to B-tree

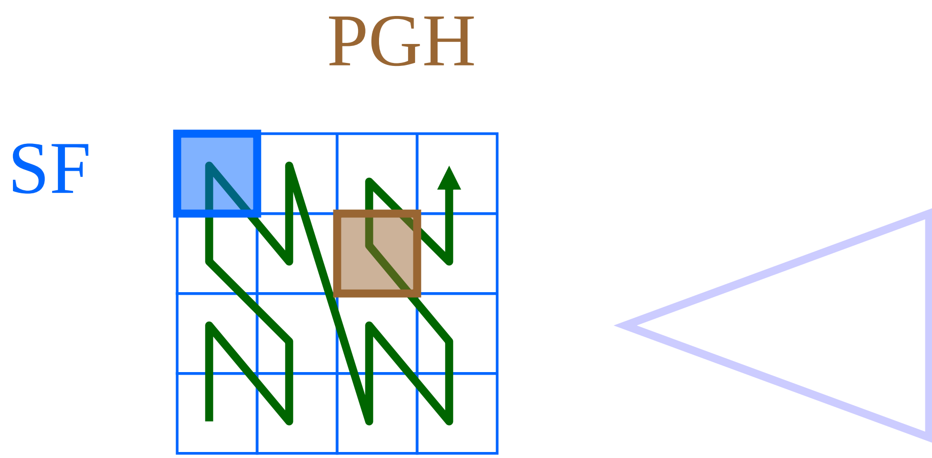


z	cname	etc
5	SF	
12	PGH	

z-ordering - usage & algo’s

MAJOR ADVANTAGES w/ B-tree:

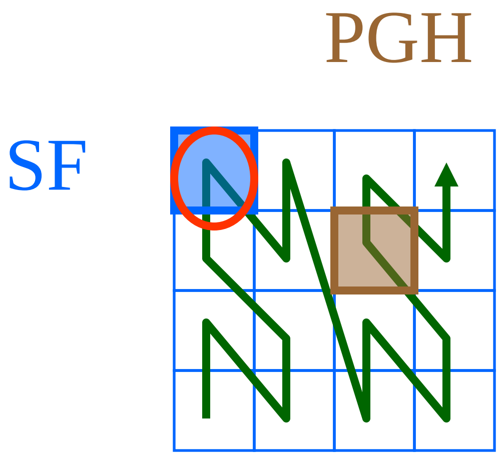
- already inside commercial systems (no coding/debugging!)
- concurrency & recovery is ready



z	cname	etc
5	SF	
12	PGH	

z-ordering - usage & algo’s

Q2: queries? (eg.: *find city at (0,3))?*

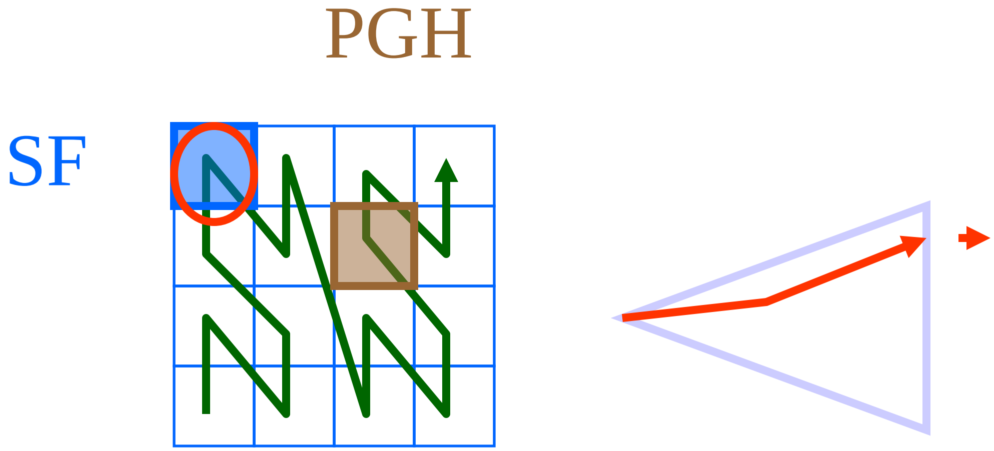


z	cname	etc
5	SF	
12	PGH	

z-ordering - usage & algo's

Q2: queries? (eg.: *find city at (0,3))*?

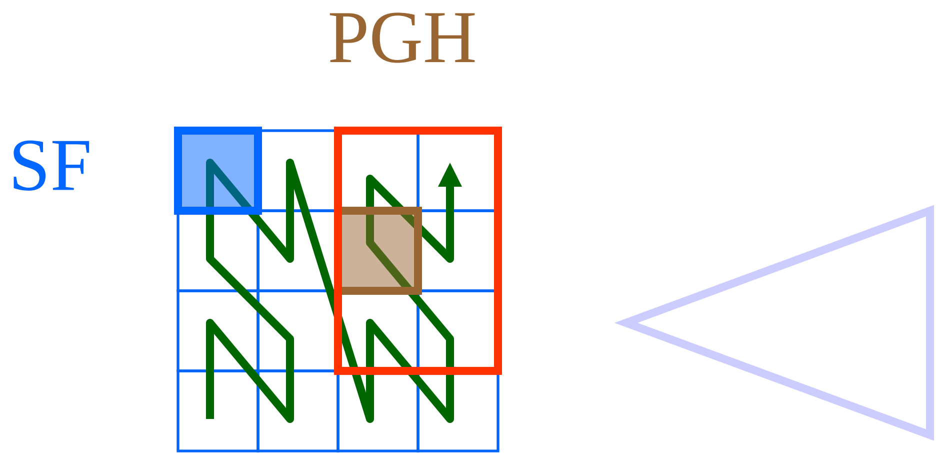
A: find z-value; search B-tree



z	cname	etc
5	SF	
12	PGH	

z-ordering - usage & algo's

Q2: range queries?

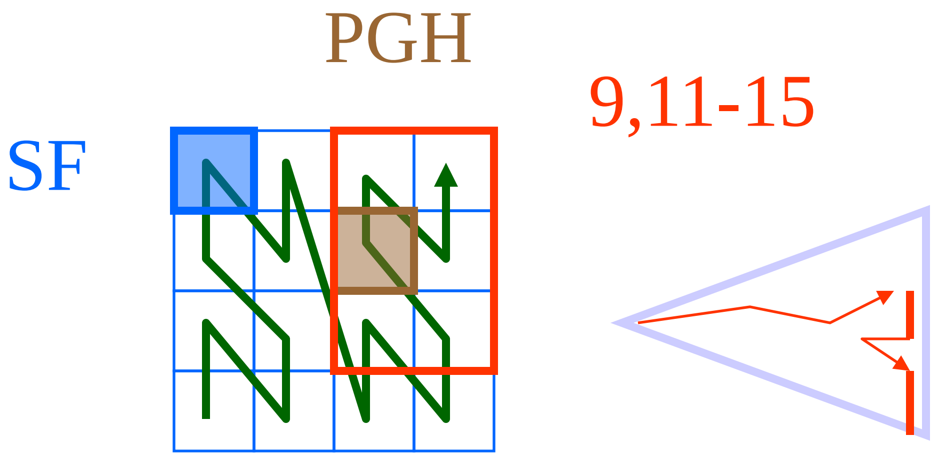


z	cname	etc
5	SF	
12	PGH	

z-ordering - usage & algo’s

Q2: range queries?

A: compute ranges of z-values; use B-tree



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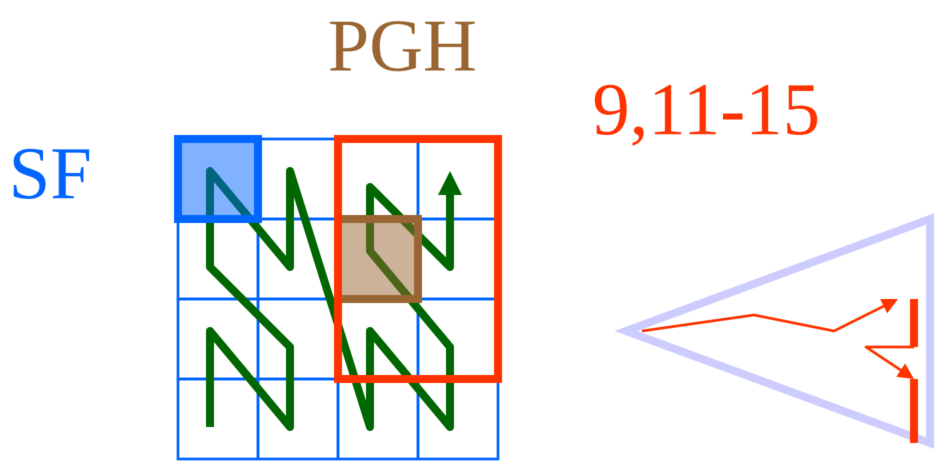
z-ordering - usage & algo's

Q2': range queries - how to reduce # of qualifying of ranges?

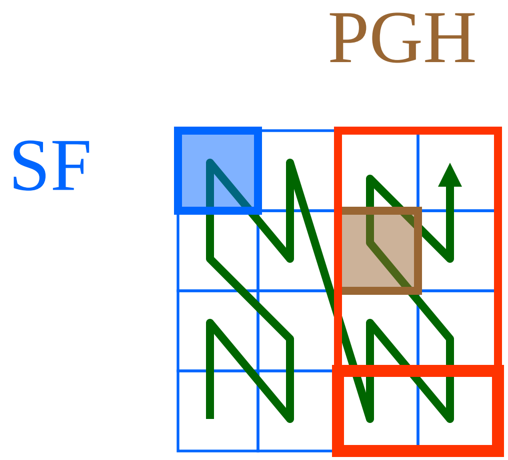


z	cname	etc
5	SF	
12	PGH	

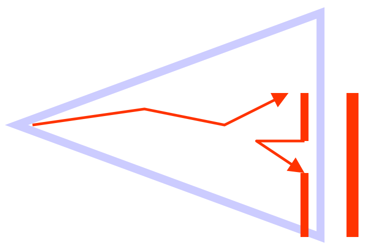
z-ordering - usage & algo's

Q2': range queries - how to reduce # of qualifying of ranges?

A: Augment the query!



9,11-15 -> **8-15**



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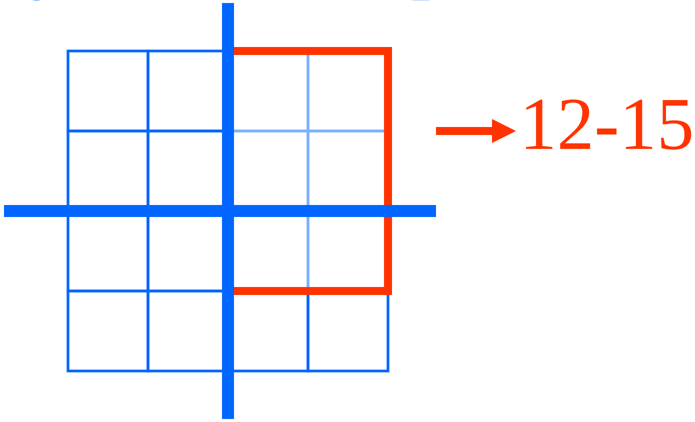
z-ordering - usage & algo's

Q2'': range queries - how to break a query into ranges?

z-ordering - usage & algo's

Q2'': range queries - how to break a query into ranges?

A: recursively, quadtree-style; decompose only non-full quadrants



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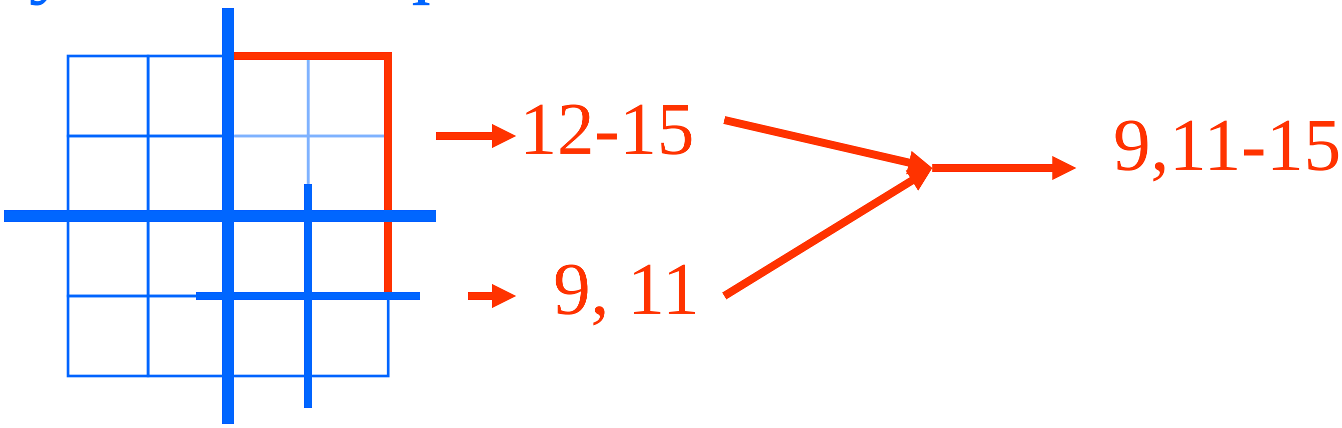

z-ordering - Detailed outline

- spatial access methods
  - z-ordering
    - main idea - 3 methods
    - use w/ B-trees; algorithms (range, knn queries ...)
    - non-point (eg., region) data
    - analysis; variations
  - R-trees

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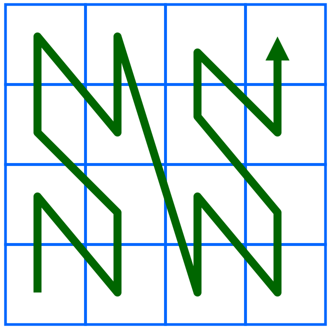
z-ordering - variations

Q: is z-ordering the best we can do?

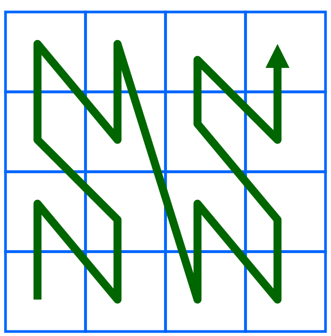


z-ordering - variations

Q: is z-ordering the best we can do?

A: probably not - occasional long ‘jumps’

Q: then?



z-ordering - variations

Q: is z-ordering the best we can do?

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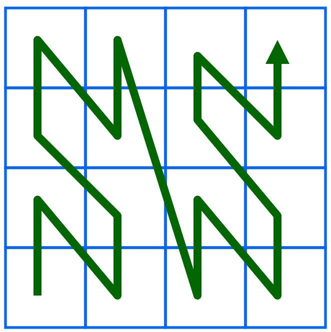
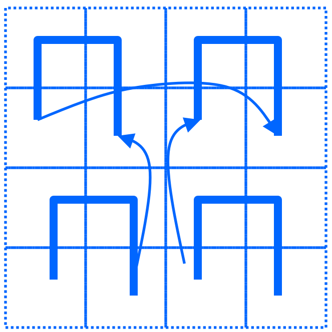
Q: then? A1: Gray codes



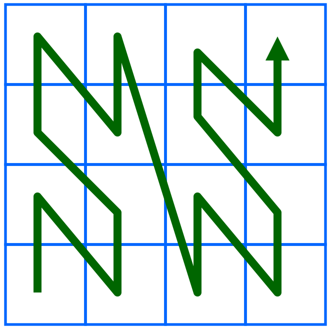


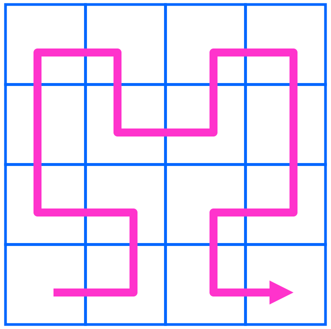
z-ordering - variations

A2: Hilbert curve! (a.k.a. Hilbert-Peano curve)

z-ordering - variations

'Looks' better (never long jumps). How to derive it?





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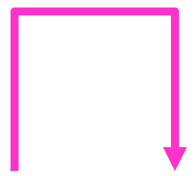
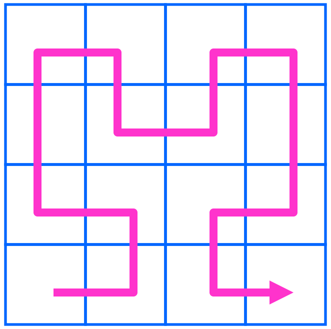
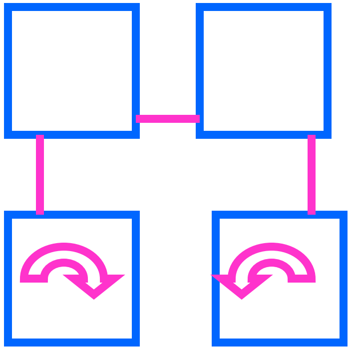


order-1



order-2



... order (n+1)

z-ordering - variations

Q: function for the Hilbert curve ($h = f(x,y)$)?

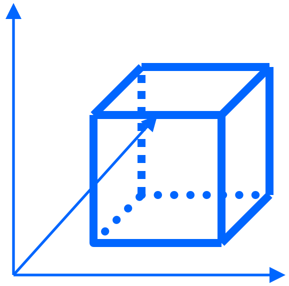
A: bit-shuffling, followed by post-processing, to account for rotations. Linear on # bits.

See textbook, for pointers to code/algorithms (eg., [Jagadish, 90])

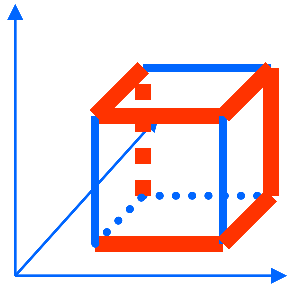
z-ordering - variations

Q: how about Hilbert curve in 3-d? n-d?

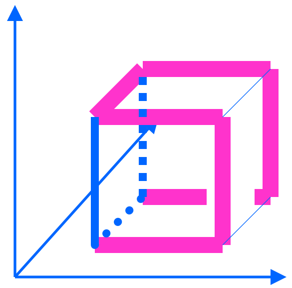
A: Exists (and is not unique!). Eg., 3-d, order-1 Hilbert curves (Hamiltonian paths on cube)



#1



#2



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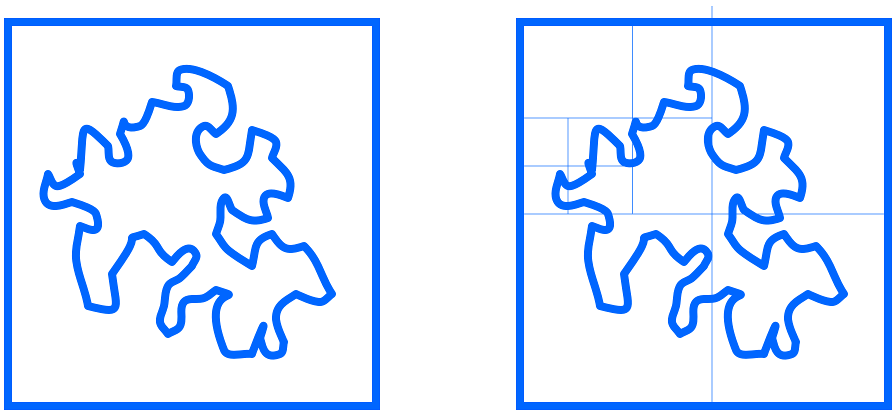
  - R-trees
  - ...

z-ordering - analysis

Q: How many pieces (‘quad-tree blocks’) per region?

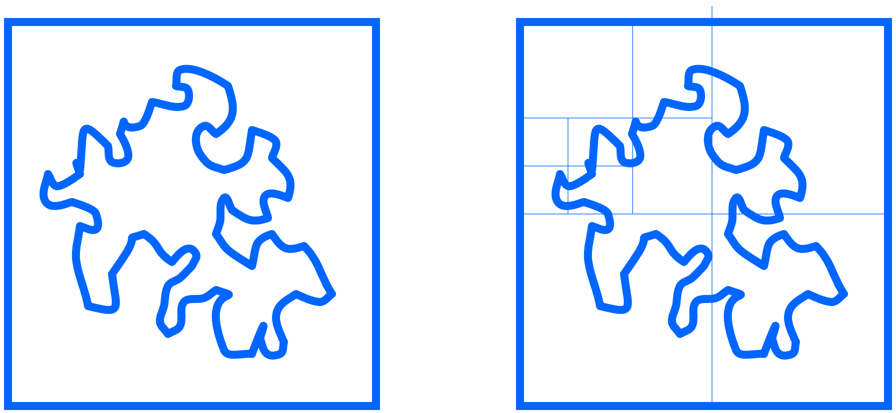
A: proportional to perimeter (surface etc)



z-ordering - analysis

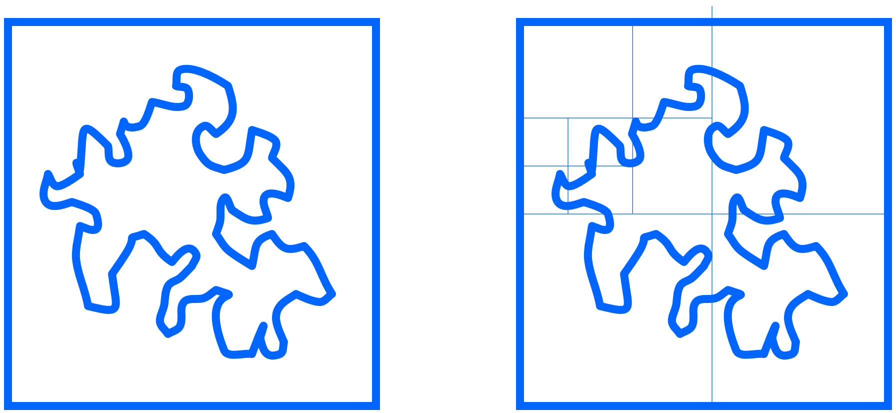
(How long is the coastline, say, of England?

Paradox: The answer changes with the yard-stick -> fractals ...)



z-ordering - analysis

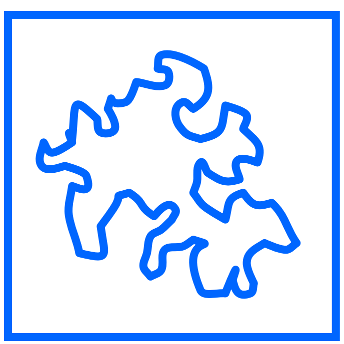
Q: Should we decompose a region to full detail (and store in B-tree)?

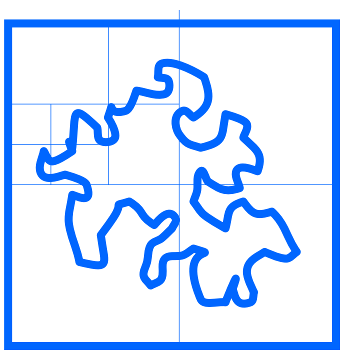


z-ordering - analysis

Q: Should we decompose a region to full detail (and store in B-tree)?

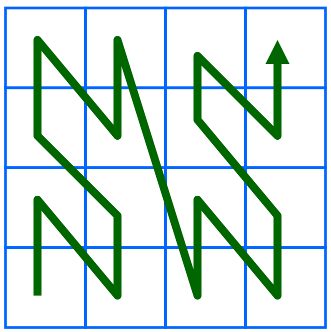
A: NO! approximation with 1-3 pieces/z-values is best [Orenstein90]

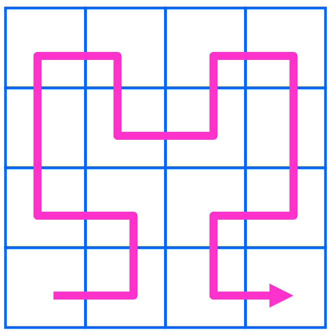




z-ordering - analysis

Q: how to measure the 'goodness' of a curve?

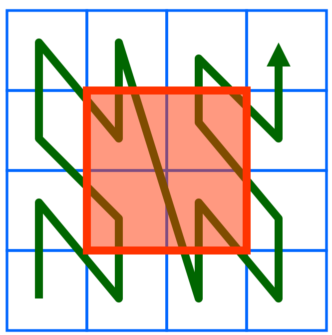


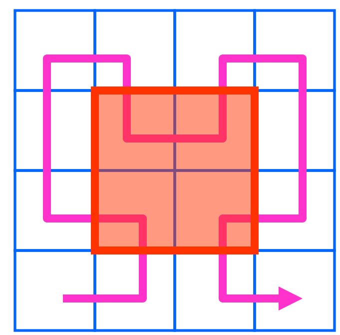


z-ordering - analysis

Q: how to measure the ‘goodness’ of a curve?

A: e.g., avg. # of runs, for range queries





4 runs 3 runs

(#runs ~ #disk accesses on B-tree)

z-ordering - analysis

Q: So, is Hilbert really better?

A: 27% fewer runs, for 2-d (similar for 3-d)

Q: are there formulas for #runs, #of quadtree blocks etc?

A: Yes ([Jagadish; Moon+ etc] see textbook)

z-ordering - fun observations

In general, Hilbert curve is great for preserving distances, clustering, vector quantization etc

Conclusions

- z-ordering is a great idea (n-d points -> 1-d points; feed to B-trees)
- used by TIGER system and (most probably) by other GIS products
- works great with low-dim points

SAMs - Detailed outline

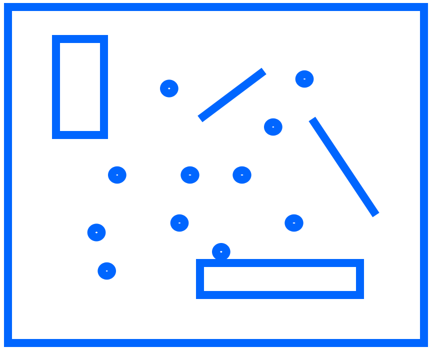
- spatial access methods
  - problem dfn
  - z-ordering
  - R-trees

SAMs - more detailed outline

- R-trees
  - main idea; file structure
  - (algorithms: insertion/split)
  - (deletion)
  - (search: range, nn, spatial joins)
  - variations (packed; hilbert;...)

Reminder: problem

- Given a collection of geometric objects (points, lines, polygons, ...)
- organize them on disk, to answer spatial queries (range, nn, etc)

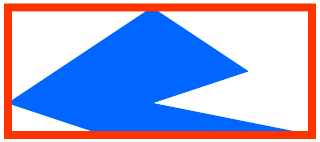


R-trees

- z-ordering: cuts regions to pieces -> dup. elim.
- how could we avoid that?
- Idea: Minimum Bounding Rectangles

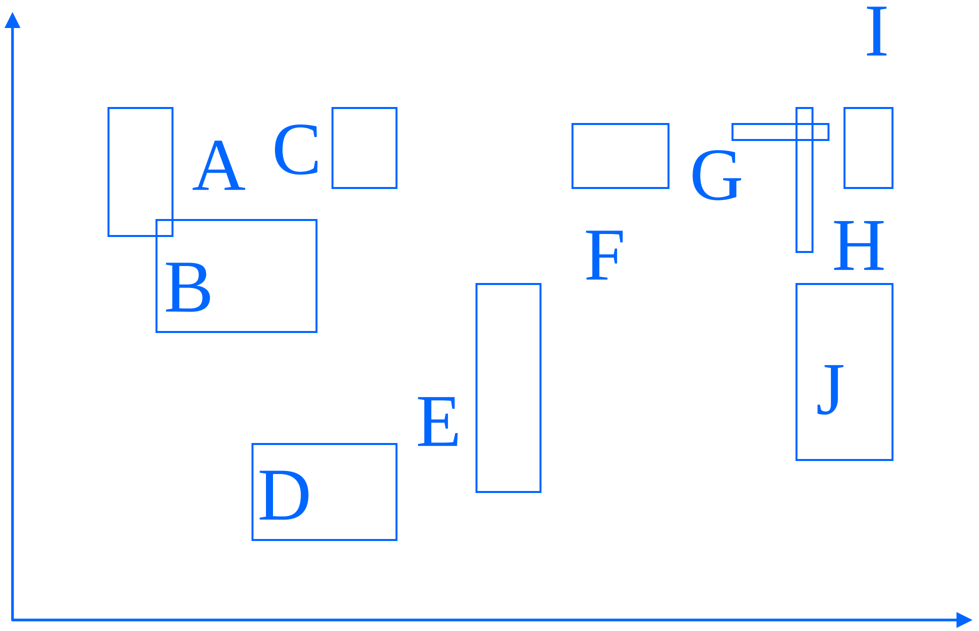
R-trees

- [Guttman 84] Main idea: allow parents to overlap!
  - => guaranteed 50% utilization
  - => easier insertion/split algorithms.
  - (only deal with Minimum Bounding Rectangles - **MBR**s)



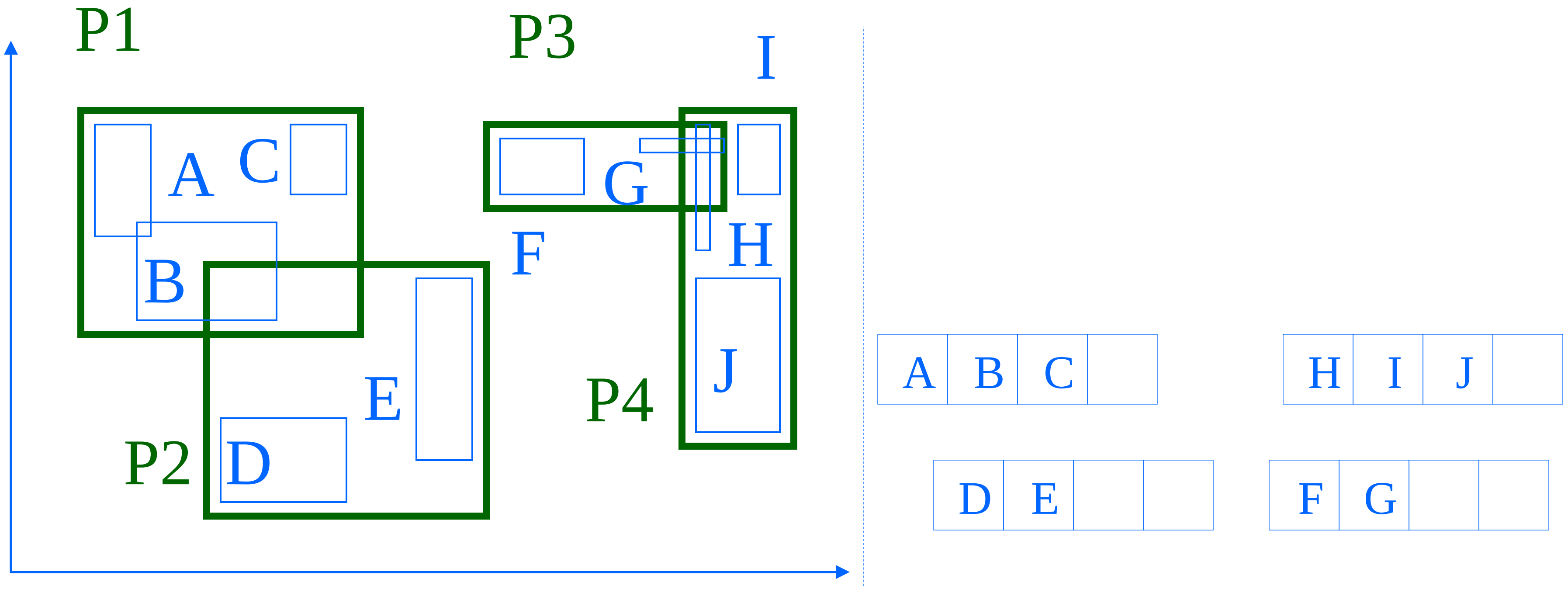
R-trees

- eg., w/ fanout 4: group nearby rectangles to parent MBRs; each group -> disk page



R-trees

- eg., w/ fanout 4:



R-trees

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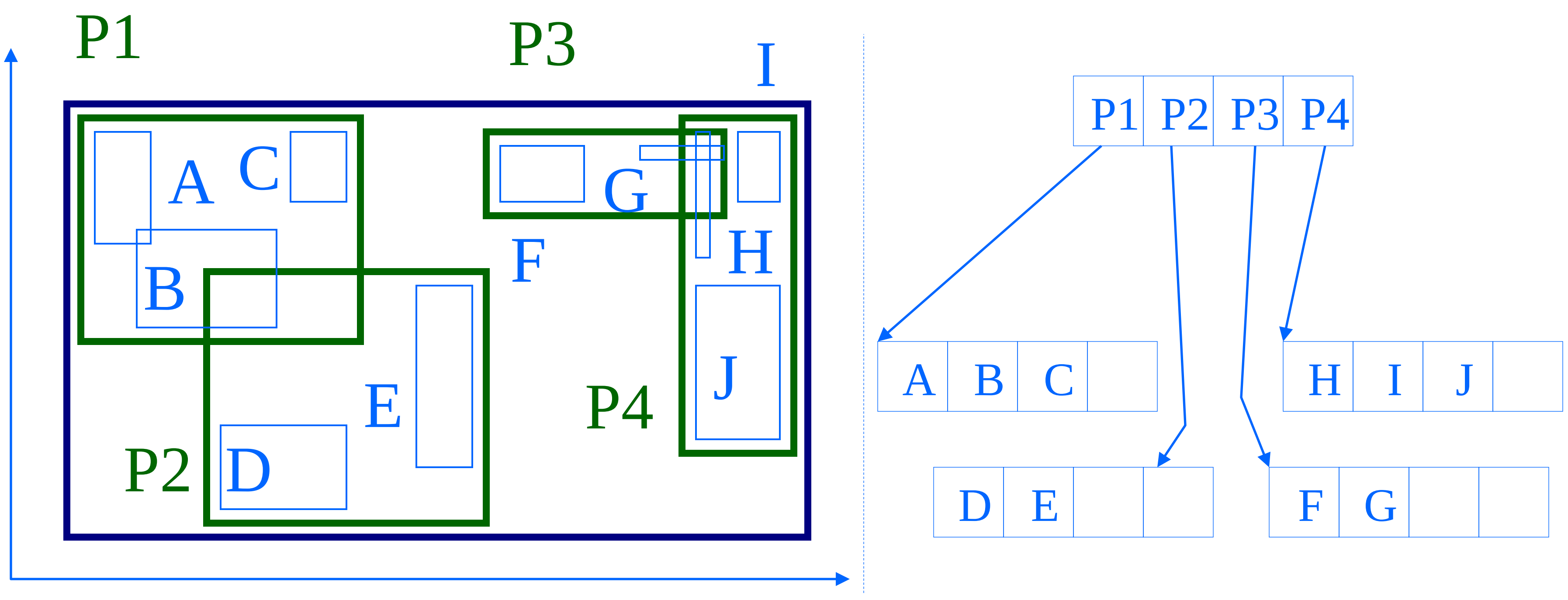
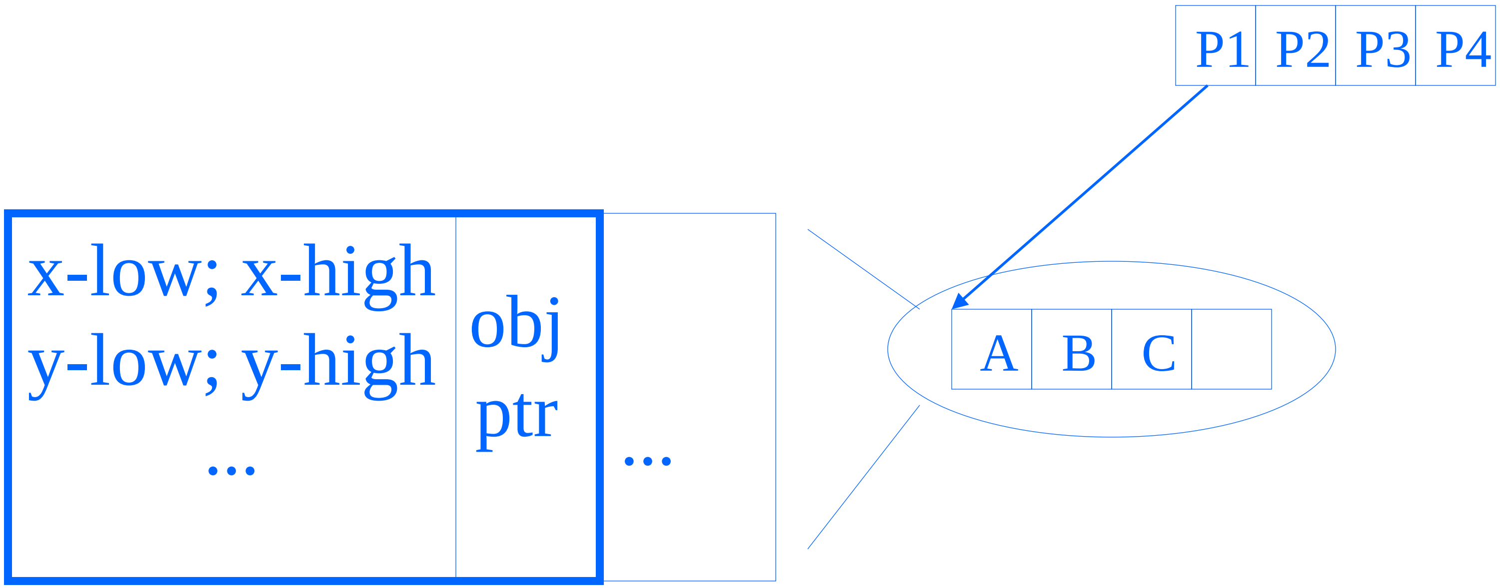


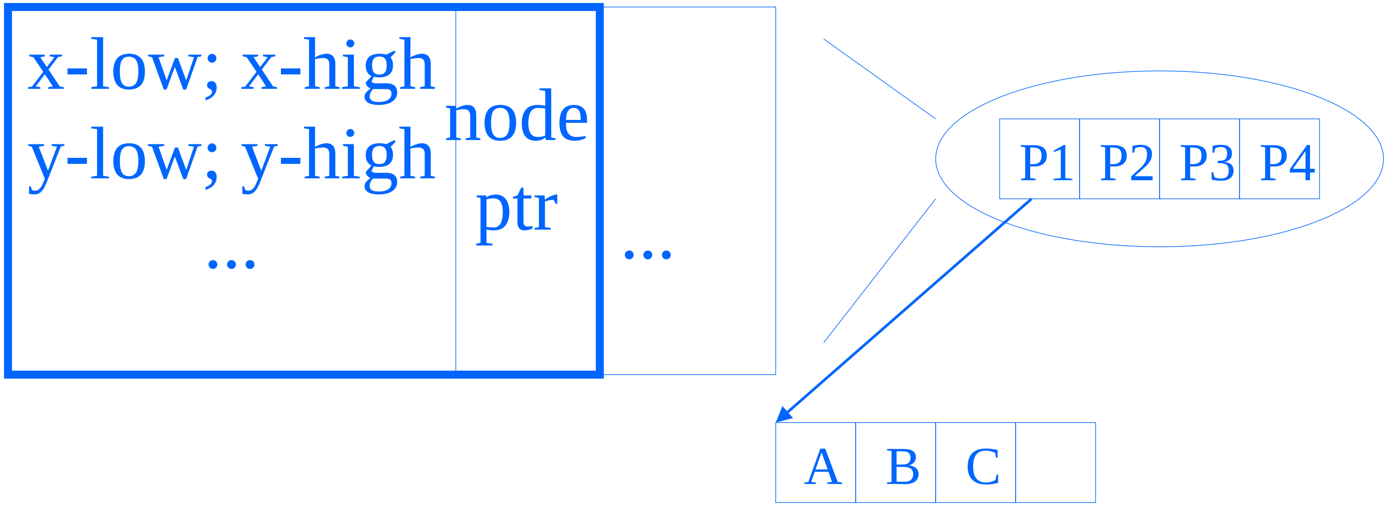
R-trees - format of nodes

- {(MBR; obj-ptr)} for leaf nodes

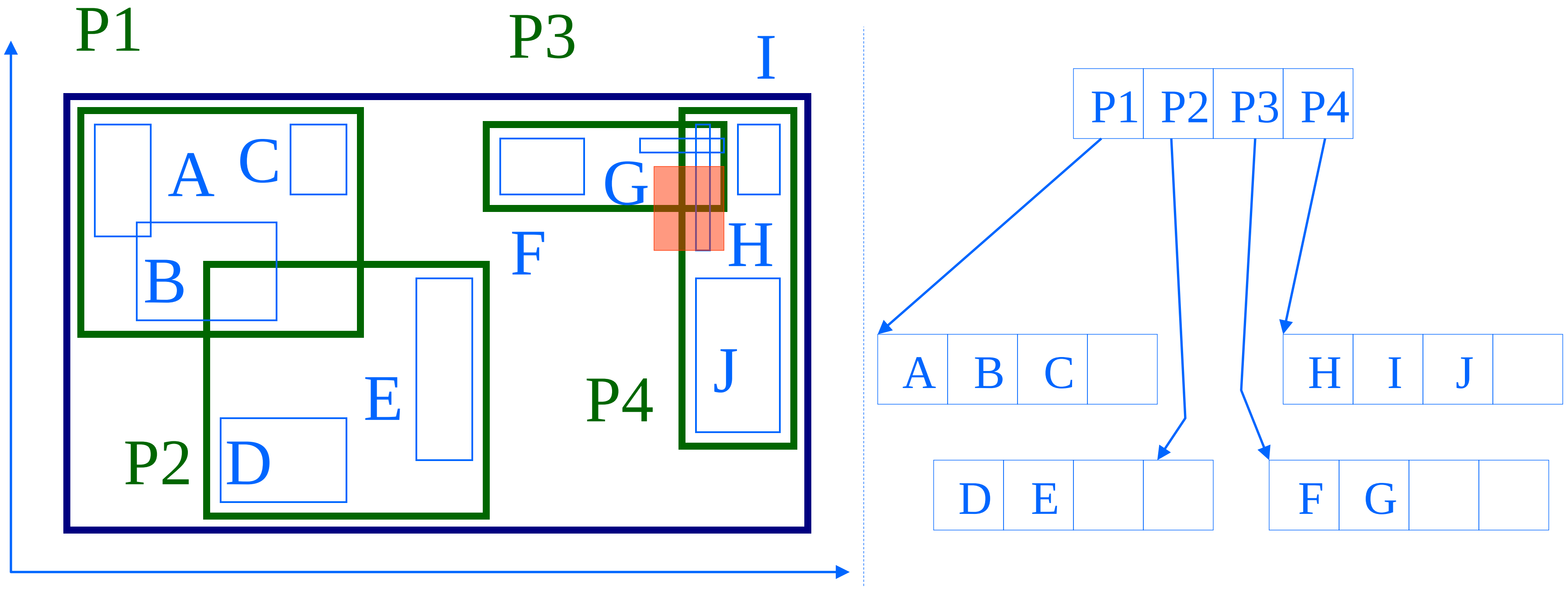


R-trees - format of nodes

- {(MBR; node-ptr)} for non-leaf nodes



R-trees - range search?



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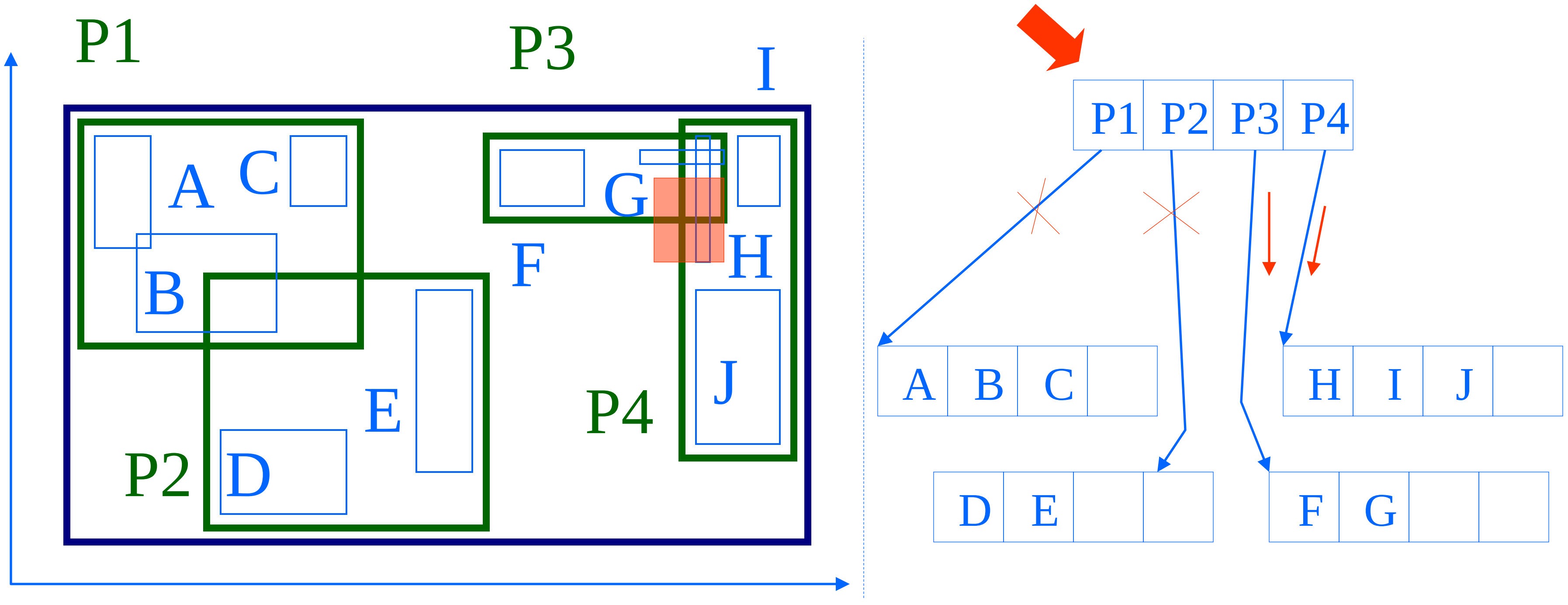


R-trees - range search

Observations:

- every parent node completely covers its ‘children’
- a child MBR may be covered by more than one parent - it is stored under ONLY ONE of them. (ie., no need for dup. elim.)

R-trees - range search

Observations - cont'd

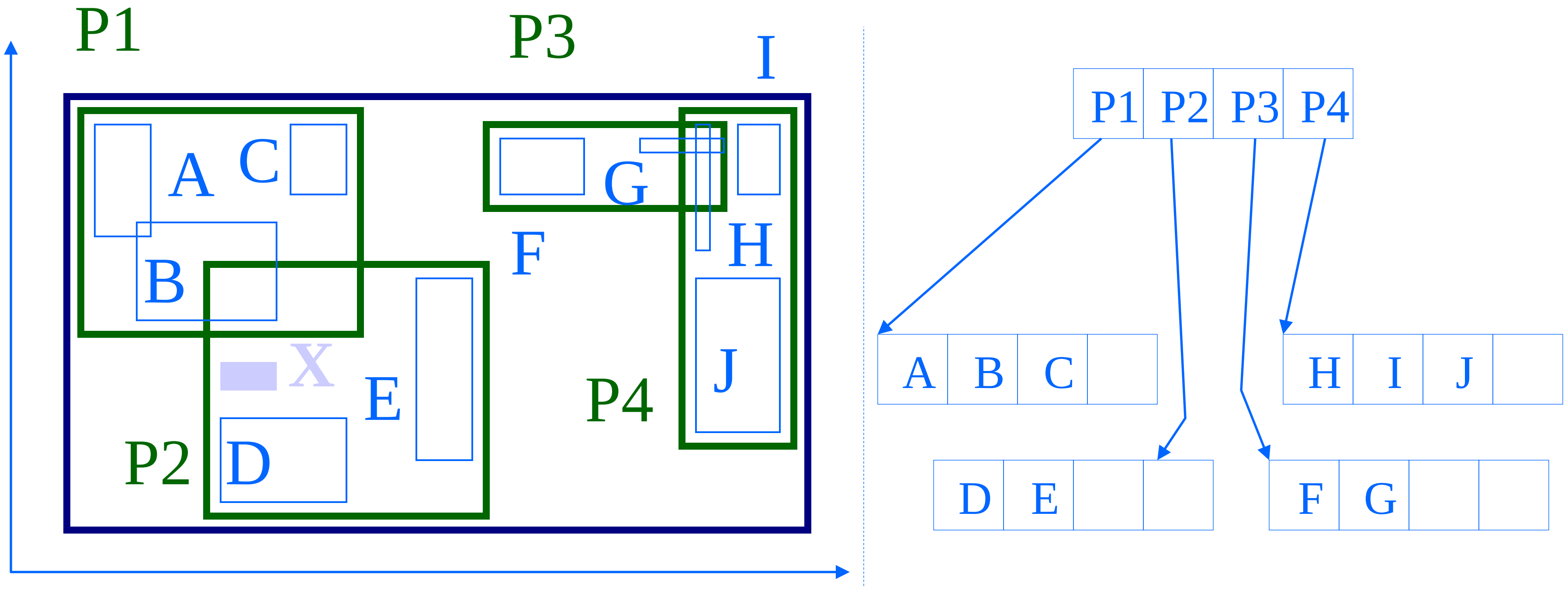
- a point query may follow multiple branches.
- everything works for **any** dimensionality

SAMs - more detailed outline

- R-trees
  - main idea; file structure
  - algorithms: insertion/split
  - deletion
  - search: range, nn, spatial joins
  - performance analysis
  - variations (packed; hilbert;...)

R-trees - insertion

- eg., rectangle 'X'



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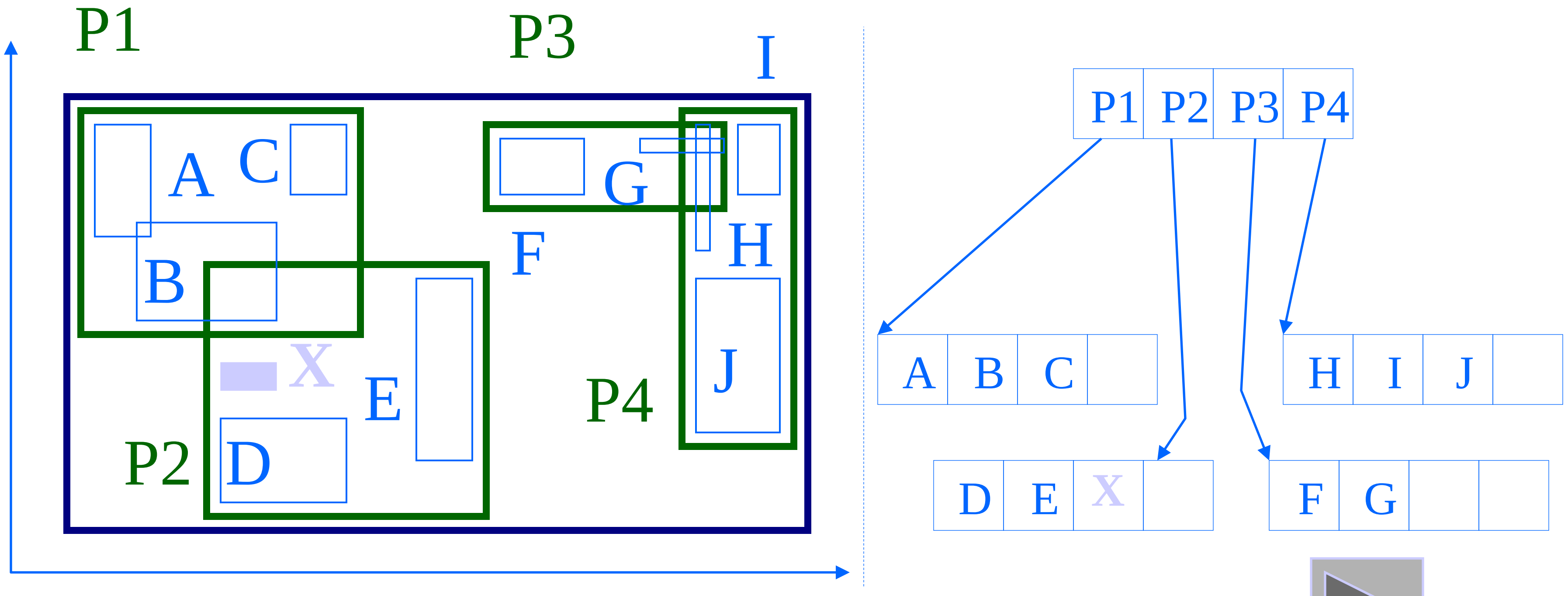

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R-trees - range search

pseudocode:

check the root

for each branch,

if its MBR intersects the query rectangle

apply range-search (or print out, if this is a leaf)

SAMs - more detailed outline

- R-trees
  - main idea; file structure
  - algorithms: insertion/split
  - deletion
  - search: range, nn, spatial joins
  - variations (packed; hilbert;...)

R-trees - variations

Guttman's R-trees sparked **much** follow-up work

- can we do better splits?
- what about static datasets (no ins/del/upd)?
- what about other bounding shapes?

R-trees - variations

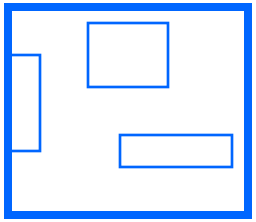
Guttman’s R-trees sparked much follow-up work

- can we do better splits?
  - i.e, defer splits?

R-trees - variations

A: R*-trees [Kriegel+, SIGMOD90]

- defer splits, by forced-reinsert, i.e.: instead of splitting, temporarily delete some entries, shrink overflowing MBR, and re-insert those entries
- Which ones to re-insert?
- How many?



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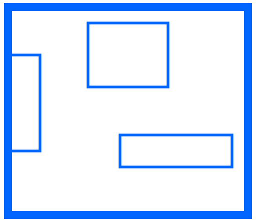
- Which ones to re-insert?
- How many? A: 30%



R-trees - variations

Q: Other ways to defer splits?

R-trees - variations

Q: Other ways to defer splits?

A: Push a few keys to the closest sibling node
 (closest = ??)

R-trees - variations

R*-trees: Also try to minimize area AND perimeter, in their split.

Performance: higher space utilization; faster than plain R-trees. One of the **most successful** R-tree variants.

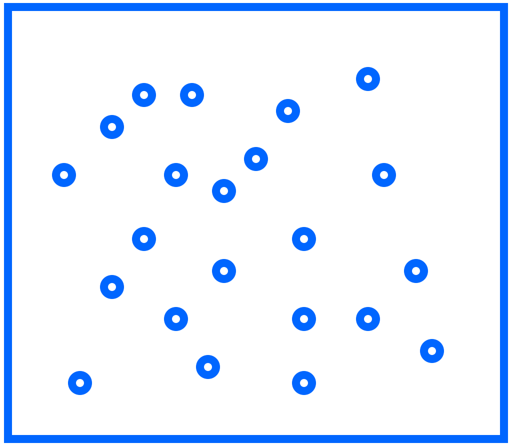
R-trees - variations

Guttman's R-trees sparked **much** follow-up work

- can we do better splits?
- ➡ what about static datasets (no ins/del/upd)?
  - Hilbert R-trees
- what about other bounding shapes?

R-trees - variations

- what about static datasets (no ins/del/upd)?
- Q: Best way to pack points?

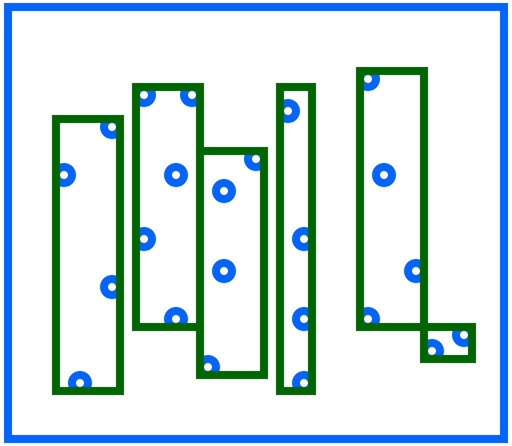


R-trees - variations

- what about static datasets (no ins/del/upd)?
- Q: Best way to pack points?
- A1: plane-sweep

  great for queries on ‘x’;

  terrible for ‘y’



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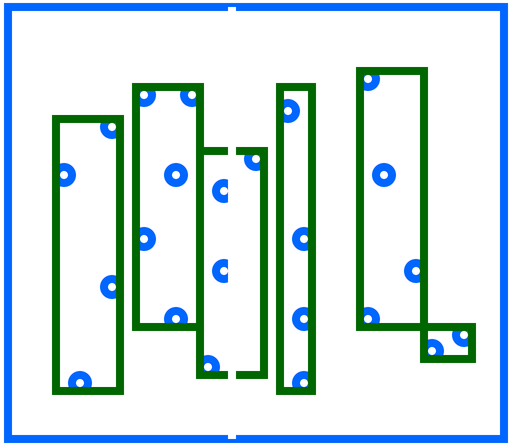

R-trees - variations

- what about static datasets (no ins/del/upd)?
- Q: Best way to pack points?
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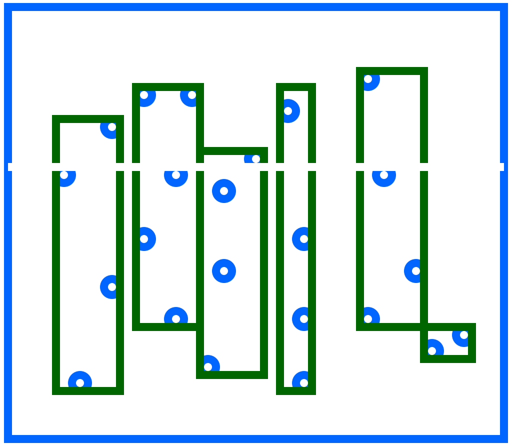
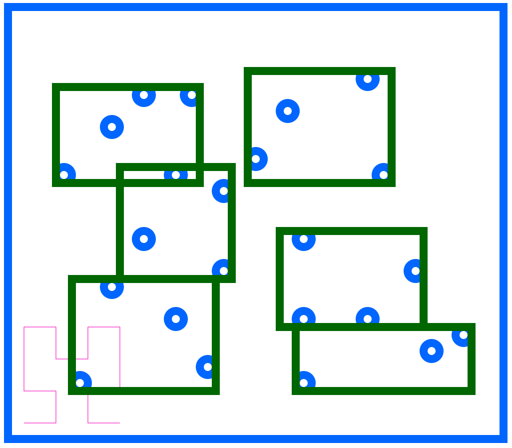
  great for queries on ‘x’;
  terrible for ‘y’
- Q: how to improve?



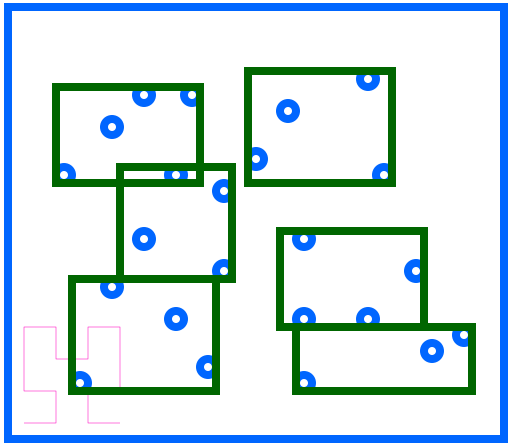
R-trees - variations

- A: plane-sweep on HILBERT curve!



R-trees - variations

- A: plane-sweep on HILBERT curve!
- In fact, it can be made dynamic (how?), as well as to handle regions (how?)
- A: [Kamel+, VLDB94]



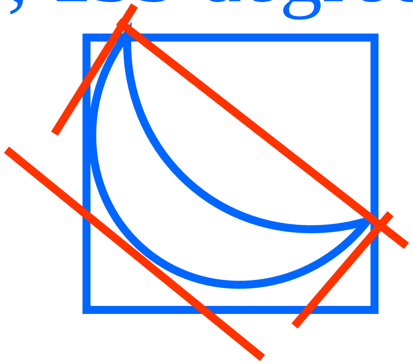
R-trees - variations

Guttman's R-trees sparked **much** follow-up work

- can we do better splits?
- what about static datasets (no ins/del/upd)?
- ➡ what about other bounding shapes?

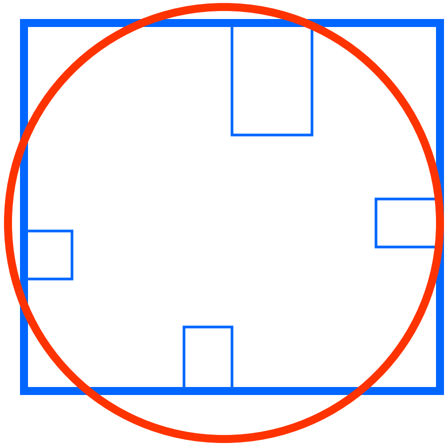
R-trees - variations

- what about other bounding shapes? (and why?)
- A1: arbitrary-orientation lines (cell-tree, [Guenther]
- A2: P-trees (polygon trees) (MB polygon: 0, 90, 45, 135 degree lines)



R-trees - variations

- A3: L-shapes; holes (hB-tree)
- A4: TV-trees [Lin+, VLDB-Journal 1994]
- A5: SR-trees [Katayama+, SIGMOD97] (used in Informedia)



R-trees - conclusions

- Popular method; like multi-d B-trees
- guaranteed utilization
- good search times (for low-dim. at least)
- R*-, Hilbert- and SR-trees: still used
- Informix ships DataBlade with R-trees

References

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