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Parallel Algorithm for Closest Pair Problem

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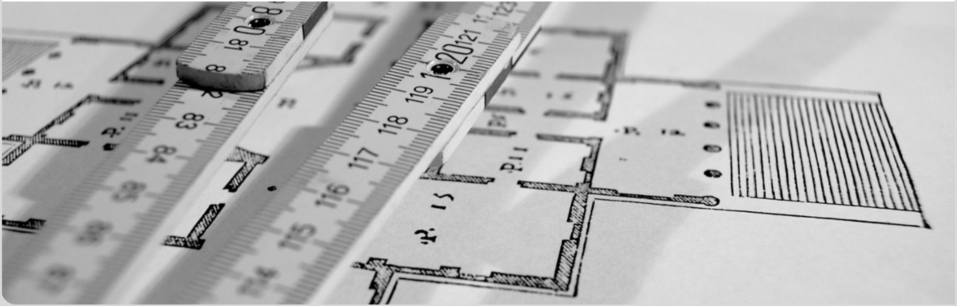
INSTITUTE FOR THEORETICAL INFORMATICS



Problem Description

Closest Pair Problem

- Given n **different** unordered points $P = \{p_1, p_2, ..., p_n\}$ in **unit square**

$$p_i = (x_i, y_i) \in (0, 1) \times (0, 1) \subset \mathbb{R}^2$$

- Find a pair of points with closest euclidean distance between them
- Find any pair if there's a tie.

Background

- $O(n \log n)$ lower bound in comparison tree model
- **Bentley and Shamos 1976**
  $O(n \log n)$ algorithm using divide and conquer
- **Rabin 1976**
  $O(n)$ randomized algorithm with $O(1)$ floor function
- **Fortune and Hopcroft 1978**
  Deterministic $O(n \log \log n)$ algorithm with $O(1)$ floor function
- **Khuller and Matias 1995**
  Another O(n) randomized algorithm

Sample

- Compute all pair of distances: $O((n^{\frac{2}{3}})^2) = O(n^{\frac{4}{3}})$
- Divide & Conquer: $O(n^{\frac{2}{3}} \log n^{\frac{2}{3}}) = O(n^{\frac{2}{3}} \log n) \subset O(n)$
  More samples possible: $O(\frac{n}{\log n} \log \frac{n}{\log n}) \subset O(n)$
- Other approach?

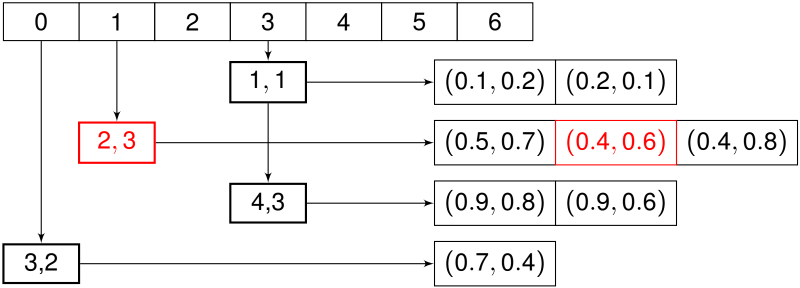
Partition

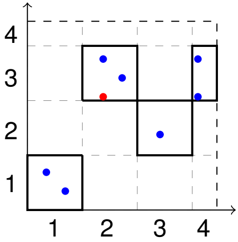
- Map points to the cells
- Divide the coordinates by cell length and truncate them to integer
- Partition $D = \{D_1, D_2, ..., D_k\}$ with:

$$\bigcup_{i=1}^{k} D_i = P, D_i \cap D_j = \emptyset, k <= n$$

- $O(n)$ with hashing

Partition





$$\boldsymbol{H}(cell_{x\_idx}, cell_{y\_idx}) = (cell_{x\_idx} + 2 \cdot cell_{y\_idx}) \mod 13$$

Compute

Compute all pairs distances

$$O(\sum_{i=1}^{k} f_i \cdot (f_i + |neighbor(G_i)|)) = O(\sum_{i=1}^{k} f_i^2) = O(n)$$

Theorem

Let $f_i = |G_i|$ with $1 \leq i \leq k$ be the number of points in i-th non-empty cell and c, d some positive constants, then

$$Prob\left(\sum_{i=1}^{k} f_i^2 <= c \cdot n\right) \geq 1 - \frac{1}{2^{n^d}}$$

Alternative for Sampling

Recursively calculate the closest distance on samples $S = \{s_1, ..., s_{n^{\frac{2}{3}}}\}$

- Sample another $n^{\frac{4}{9}}$ points S' from S
- Get closest distance on S' by calculating all pair distances: $O(n^{\frac{8}{9}})$
- Partition and compute the closest distance on S

Pseudocode

0 Cell set $H = \emptyset$, Result $rst = \infty$

1 Choose set S of $n^{\frac{2}{3}}$ samples $O(n^{\frac{2}{3}})$

$\delta = min_{x,y \in S, x \neq y}(dist(x, y))$ $O(n^{\frac{8}{9}})$

2 **for** $i = 1$ **to** n **do** $O(n)$

$\quad c = cell(p_i)$

$\quad$ **if** *not* $H.findCell(c)$ **then**

$\quad\quad H.addCell(\{c, idx = \{c.x, c.y\}\}$

$\quad H.findCell(c).addPoint(p_i)$

3 **foreach** c_1 **in** H **do** $O(n)$

$\quad$ **foreach** c_2 **in** $\{c_1\} \cup neighbor(c_1)$ **do**

$\quad\quad$ **foreach** (p_i, p_j) **in** $c_1 \times c_2$

$\quad\quad\quad rst = min(rst, dist(p_i, p_j))$

Runtime: $O(n)$ with high probability

Worst case: $O(n^2)$

Parallelization

0 Cell set $H = \emptyset$, Result $rst = \infty$ ## H synchronized Hashmap

1 Choose set S of $n^{\frac{2}{3}}$ samples ## allocate p PEs — $O(n^{\frac{2}{3}}/p)$

$\delta = min_{x,y \in S, x \neq y}(dist(x,y))$ ## recurse once — $O(n^{\frac{8}{9}} + \log p)$

2 **for** $i = 1$ **to** n **do** ## allocate p PEs — $O(n/p)$

$c = cell(p_i)$

if *not* $H.findCell(c)$ **then**

$H.addCell(\{c, idx = \{c.x, c.y\}\}$ ## maximal n times

$H.findCell(c).addPoint(p_i)$

3 **foreach** c_1 **in** H **do** — $O(n/p + \log p)$

foreach c_2 **in** $\{c_1\} \cup neighbor(c_1)$ **do**

foreach (p_i, p_j) **in** $c_1 \times c_2$ ## allocate $\lfloor p \cdot \frac{\#Pairs}{|c_1||c_2|} \rfloor$ PEs

$rst = min(rst, dist(p_i, p_j))$

Total runtime: $O(\frac{n}{p} + \log p)$

$\log p$ for collecting minimal distance from all processors

Proof Sketch

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Theorem

Let $\mathbf{f_i} = |G_i|$ with $1 \leq i \leq k$ be the number of points in i-th non-empty cell and c, d some positive constants, then

$$Prob\left(\sum_{i=1}^{k} f_i^2 <= c \cdot n\right) \geq 1 - \frac{1}{2^{n^d}}$$

Proof Sketch

Sampling Lemma

Let $D = \{D_1, D_2, ..., D_k\}$ be a partition of set P, $|P| = n$, for which $N(D) \geq n$, where

$$N(D) = \sum_{i=1}^{k} \frac{|D_i| \cdot (|D_i| - 1)}{2}$$

If $n^{\frac{2}{3}}$ pairwise different elements are drawn at random from P then the probability, that two elements will be chosen from the same D_i, is at least $1 - 2^{-n^c}$ for some positive constant c

Proof see

- **Rabin 1976**
- **Dietzfelbinger et al. 1997**
  Estimate the probability using Chebyshev's inequality

Proof Sketch

Lemma 2

Let G_δ be a grid with gap δ and $G_{2\delta}$ another grid with gap 2δ, which is obtained by ignoring every second line of G_δ, then

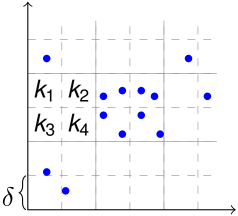
$$N(G_{2\delta}) \leq 4N(G_\delta) + \frac{3}{2}n$$

Let $k = \sum_{i=1}^{4} k_i$

$f(x) = x(x-1)$ convex $\Rightarrow f(\frac{1}{4}k) \leq \frac{1}{4}\sum_{i=1}^{4} f(k_i)$

$$\begin{aligned}\frac{1}{2}k(k-1) &= 8 \cdot \frac{1}{4}k(\frac{1}{4}k - 1) + \frac{3}{2}k \\ &\leq 8 \cdot \frac{1}{4}\sum_{i=1}^{4} k_i * (k_i - 1) + \frac{3}{2}k\end{aligned}$$

$\Rightarrow N(G_{2\delta}) \leq 4N(G_\delta) + \frac{3}{2}n$



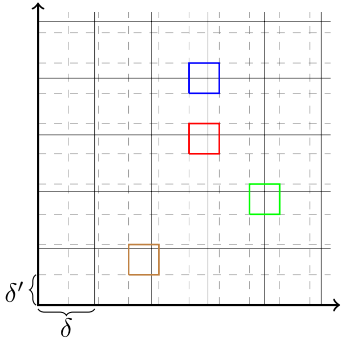
Proof Sketch

Lemma 3

For any grid G_δ, $G_{\delta'}$ with $\delta' \leq \delta$ the following applies

$$N(G_{\delta'}) \leq 16N(G_\delta) + 6n$$

$$\begin{aligned} N(G_{\delta'}) &\leq \sum_{i=1}^{4} N(G_{2\delta}^{i}) \\ &\leq \sum_{i=1}^{4} (4N(G_\delta) + \tfrac{3}{2}n) \\ &= 16N(G_\delta) + 6n \end{aligned}$$



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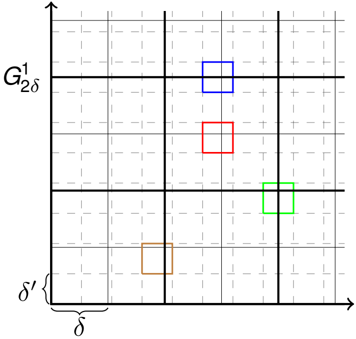

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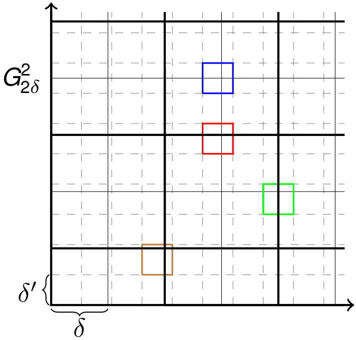

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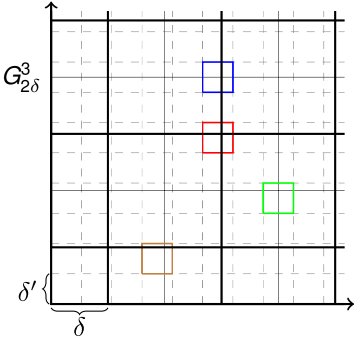
$$\begin{aligned} N(G_{\delta'}) &\leq \sum_{i=1}^{4} N(G^i_{2\delta}) \\ &\leq \sum_{i=1}^{4} (4N(G_\delta) + \tfrac{3}{2}n) \\ &= 16N(G_\delta) + 6n \end{aligned}$$



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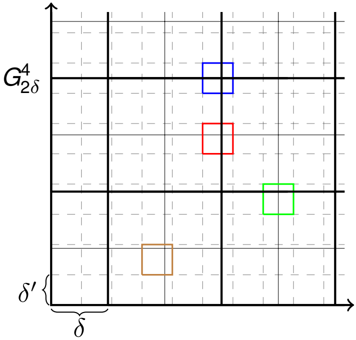

Proof Sketch

- Two of $n^{\frac{2}{3}}$ samples will be very likely in the same cell, if $N(G) \geq n$
- $N(G_{2\delta}) \leq 4N(G_{\delta}) + \frac{3}{2}n$
- $N(G_{\delta'}) \leq 16N(G_{\delta}) + 6n \qquad$ if $\delta' \leq \delta$

Proof.

Let δ^* be the grid gap, which makes $n \leq N(G_{\delta^*}) < 5.5n$. (It exists!)
If $n^{\frac{2}{3}}$ samples are randomly chosen, two of them will be in one cell with high probability. Let δ be the distance between them and $\delta < 2\delta^*$, then

$$\begin{aligned} N(G_{\delta}) &\leq 16N(G_{2\delta^*}) + 6n \\ &\leq 16N(4N(G_{\delta^*}) + \frac{3}{2}n) + 6n \\ &\in O(n) \end{aligned}$$

$\square$

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Reference III

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