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$\Omega(B_i/2 \cdot D_i) = \Omega(n)$. In either case we have shown that the cost of a phase is $\Omega(n)$. Since there are $\log^* n$ phases, the lower bound follows. ∎

In Lemma 29, player A chooses balls so as to make the life for player B as difficult as possible. In RIC's objects are chosen randomly. Let us say that player A plays *randomly* if she always chooses a random white ball.

Lemma 30 *If A plays randomly, then the expected cost of the game is $\Omega(n \log^* n)$.*

Proof: Define the division into phases as in Lemma 29. At the end of the i–th phase there are B_i black balls. These balls from a random subset of $[1\,..\,n]$. In order to lower bound the expected cost of the i–th phase we change the rules of the game in B's favor: At the end of the i–th phase, player B selects $B_i/2$ black balls and declares that A's moves in the i–th phase involving these balls are free of charge.

We now distinguish two cases. For the remaining $B_i/2$ balls which are black at the end of the i–th phase, either at least $B_i/4$ were relabeled by B before A selects the ball, or this is not the case. In the former case, the cost of B's moves is clearly lower bounded by the sum of the $B_i/4$ smallest distances between black balls. The expected value of this sum is $\Omega(n)$. In the latter case, the cost of A's moves is $\Omega(n)$. ∎

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cost, B tries to minimize it.

The intended relationship to RIC is as follows: A ball is black if it belongs to R. The label of a ball is i if the ball knows its conflicts with the regions in $\mathcal{F}_0(R_i)$. A move of player A moves a ball from time r_{old} in the history to time r and a move of player B moves an interval of points to the latest time in history occurring in the interval. In the algorithms mentioned above, the interval is always the entire sequence of balls. Player A models the process which generates the insertion sequence. We will consider two strategies for player A in the sequel: a deterministic strategy which maximizes cost and a random strategy where she always selects a random white ball. Player B models the algorithm and its ability to move an entire interval of points to a later time in history.

Let $L = \log^* n = \max\{i; \log^{(i)} n > 1\}$, $D_i = \log^{(i)} n$ for $1 \le i \le L$, $D_{L+1} = 1$, and $D_0 = n + 1$. Let $B_i = \lfloor n/D_i \rfloor$ for $0 \le i \le L + 1$.

Lemma 28 *Player B can keep the cost in $O(n \log^* n)$.*

Proof: B plays the following simple strategy. In its B_i–th turn, $1 \le i \le L$, B relabels the complete sequence of balls. The total cost of B's moves is $nL = n \log^* n$. The total cost of A's moves is

$$\le \sum_{0 \le i \le L} (B_{i+1} - B_i) \log(B_{i+1}/\max\{B_i, 1\}) = O(n \log^* n) ,$$

since $(B_{i+1} - B_i) \log(B_{i+1}/ \max\{B_i, 1\}) = O(B_{i+1} \log D_i/D_{i+1}) = O((n/D_{i+1}) \log D_i) = O(n)$. ∎

Lemma 29 *Player A can force the cost into $\Omega(n \log^* n)$.*

Proof: We first describe the strategy of player A. A's game is divided into phases; the i–th phase, $1 \le i \le L + 1$, consists of moves $B_{i-1} + 1$ to B_i. In the i–th phase, A labels all multiples of D_i which are not multiples of D_{i-1}. We assume here that the balls are numbered 1 through n.

We show that the total cost of A's and B's moves in the i–th phase is $\Omega(n)$. Call a multiple of D_i interesting if A labels it by one of the moves $B_i/2 + 1$ to B_i. If for more than $1/2$ of the interesting balls the cost of A's move is $\log((B_i/2)/ \max(1, B_{i-1}))$, then the total cost of A's moves in the i–th phase is $\Omega(B_i/2 \cdot \log(D_{i-1}/D_i)) = \Omega(B_i \cdot (D_i - D_{i+1})) = \Omega(n)$. Otherwise, more than half of the interesting points must have been relabeled in the i–th phase by a move of B, since all interesting points have label at most B_{i-1} at the beginning of the i–th phase. Since an interesting point has distance D_i from any point touched by A in the i–th phase, the total cost of B's moves must be at least

of different facets that intersect ℓ during the course of the incremental construction. We have $b = d$ and $|\mathcal{F}_0(R)| \leq 1$ for all R. Thus we can use $M(r) = d$. It is easy to check that $E[X] = dH_n$. Applying Corollary 25 and approximating H_n by $\log n$ now yields that the probability that X exceeds c times its expectation is $O(n^{-(1+c\log(c/e))})$.

Note that the facet changes discussed here correspond by duality to the minimum changes at the top level of the randomized incremental linear programming algorithm in [Sei91]. This implies that the probability for that algorithm to have more than a logarithmic number of minimum changes at the top level is exceedingly small. Carrying this further, this implies that the probability for that algorithm to bottom out with constant sized problems more than $O(\log^d n)$ times is also very small.

5 A game related to some randomized incremental constructions

Seidel [Sei91] gave a randomized $O(n \log^* n)$ algorithm for the triangulation of simple polygons. Devillers [Dev] recently extended the approach to other problems, e. g., the construction of the Voronoi–diagram for the edges of a simple polygon. The idea behind the $O(n \log^* n)$ is as follows: When an object $x \in S - R$ is added to R in standard RIC, the object x traces through the history of the construction. This takes time $O(\log r)$ for the r–th object to be inserted (apply Theorem 4 with $f_j = O(j)$). On the other hand, in the two examples mentioned above, all conflicts between objects in $S - R$ and regions in $\mathcal{F}_0(R_i)$ can be computed in expected linear time. Seidel and Devillers therefore interrupt the standard algorithm at suitable breakpoints , say after the i–th insertion, and compute all conflicts between $S - R_i$ and $\mathcal{F}_0(R_i)$. The crucial observation is now that if object $x_k \in S - R_i$ knows its conflicts with the regions in $\mathcal{F}_0(R_i)$ then its conflicts with the regions in $\mathcal{F}_0(R_{k-1})$ can be computed in additional $O(\log(k/i))$ expected time; sum the bound in Lemma 5 for j between i and k to see that only $O(\log(k/i))$ additional conflicts exist on average. A suitable choice of breakpoints yields an $O(n \log^* n)$ algorithm. Can this approach yield linear time algorithms? The following game is supposed to shed some light on this question.

The game is played on a sequence of n balls. Initially, all balls have label 1 and color white. There are two players A and B who take turns. The game stops when all balls are black. In her r–th turn player A selects a white ball, turns it black and labels it r. The cost of this move is $\log(r/r_{old})$, where r_{old} is the previous label of the ball. In her turn, B performs one or more of the following move: She selects an interval (i.e. a contiguous subsequence) of balls and relabels all balls in the interval with the highest label occurring in the interval. The cost of the move is the length of the interval. A tries to maximize

Proof: If $M(i)/i$ is non–decreasing, then for all $x \geq 1$ we have $\frac{1}{i}(x^{M(i)}-1) \leq \frac{1}{n}(x^{M(n)}-1)$ for each $i \leq n$. (The polynomial $\frac{1}{n}(x^{M(n)}-1) - \frac{1}{i}(x^{M(i)}-1)$ has a root at $x = 1$ and nonnegative derivative for $x \geq 1$.) Therefore

$$\Pr[X \geq cM(n)] \leq \frac{e^{\sum_{1\leq i\leq n} \frac{1}{i}(x^{M(i)}-1)}}{x^{cM(n)}} \leq \frac{e^{\sum_{1\leq i\leq n} \frac{1}{n}(x^{M(n)}-1)}}{x^{cM(n)}} = \frac{e^{x^{M(n)}-1}}{x^{cM(n)}} .$$

Now choose x such that $x^{M(n)} = c$. ∎

For many RICs, e.g., the construction of convex hulls (in any dimension) ([CS89] and this paper), Delauney triangulations ([GKS90]), abstract Voronoi diagrams ([MMO91]), trapezoidal diagrams for non–intersecting line segments ([CS89, Sei91]), spherical intersections ([CS89]) and the construction of a single face of an arrangement ([CEG+91]), there is a function $M(r)$ such that $M(r)/r$ is non-decreasing, $b|\mathcal{F}_0(R)| \leq M(r)$ when $|R| = r$, and $M(r) \leq dC_r$ for some small constant d. In these situations, Corollary 26 bounds the probability that the size of the history exceeds its expected value by a constant factor.

As a particular example consider the randomized incremental construction of the convex hull of n points in $\mathbb{R}^3$ as discussed in the previous section. The random variable X here denotes the number of facets created during the incremental construction. The quantity $|\mathcal{F}_0(R)|$ is the number of facets of a 3-dimensional polytope with r vertices, which is at most $2r - 4$. We have $b = 3$, and therefore we can use $M(r) = 6r$. Chasing through the definitions at the beginning of the previous section and applying Theorem 3 yields that $E[X] < 6n = M(n)$. Applying now Corollary 26 yields that the probability that X exceeds c times its expectation is less than $(1/e) \cdot (e/c)^c$.

The following Corollary of Theorem 25 is also be useful.

Corollary 27 *If $M(i) = m_0$ for all i, then $\Pr[X \geq cm_0H_n] \leq e^{-H_n(1+c\log(c/e))}$ for $c > 1$, where H_n is the n–th harmonic number.*

Proof: From Theorem 25 we get

$$\Pr[X \geq cm_0H_n] \leq \frac{e^{\sum_{1\leq i\leq n} \frac{1}{i}(x^{m_0}-1)}}{x^{cm_0H_n}} = \frac{e^{H_n(x^{m_0}-1)}}{x^{cm_0H_n}} .$$

Now choose x such that $x^{m_0} = c$ to obtain the desired result. ∎

As an example here again consider randomized incremental convex hull construction in $\mathbb{R}^d$ as described in the previous section, but restrict attention to only those facets that intersect a fixed ray ℓ emanating from the origin O. Assuming non-degeneracy this ray intersects at most one facet of any conv R during the construction. Let X be the random variable that counts the number

Claim 24 *For all $x > 1$ we have*

$$p(x) \leq p_n(x) := \prod_{1 \leq i \leq n} \left(1 + \frac{1}{i}(x^{M(i)} - 1)\right) .$$

Proof: We use induction on n, the size of S, looking at corresponding generating functions for subsets of S. The claim holds vacuously for $n = 0$.

For the random permutation π of S, we know that y_n is a random element of S, and so

$$p(x) = p_S(x) = \frac{1}{n} \sum_{y \in S} x^{deg(y,S)} p_{S \setminus \{y\}}(x).$$

Applying the inductive assumption to every $(n-1)$-element subset of S, we get

$$p(x) \leq \frac{p_{n-1}(x)}{n} \sum_{y \in S} x^{deg(y,S)}.$$

Since

$$\sum_{y \in S} deg(y, S) \leq b|\mathcal{F}_0(S)| \leq M(n),$$

the power sum is maximized for $x > 1$ when $deg(y, S) = M(n)$ for some $y \in S$ and the degrees of the other members of S are zero. Thus

$$p(x) \leq \frac{p_{n-1}(x)}{n} \left(x^{M(n)} + (n-1)\right) = \left(1 + \frac{1}{n}(x^{M(n)} - 1)\right) p_{n-1}(x) = p_n(x) .$$

∎

Theorem 25 *For any integer $M \geq 0$ and any real $x \geq 1$*

$$\Pr[X \geq M] \leq \frac{\prod_{1 \leq i \leq n} \left(1 + \frac{1}{i}(x^{M(i)} - 1)\right)}{x^M} \leq \frac{e^{\sum_{1 \leq i \leq n} \frac{1}{i}(x^{M(i)} - 1)}}{x^M} .$$

Proof: This follows from Fact 23 and Claim 24, using the inequality $1 + x \leq e^x$.

∎

Corollary 26 *If $M(i)/i$ is non–decreasing, then for all $c > 1$*

$$\Pr[X \geq cM(n)] \leq (1/e) \cdot (e/c)^c .$$

Theorem 22 *The expected time to delete a random point from the convex hull of n points (constructed by random insertions) is*

$$O\left(\min\left\{n, \left(d + d^2 \sum_{i\leq n} f_i/(i\cdot n)\right)\log\log n\right\} + d^4 \sum_{i\leq n} f_i/(i\cdot n) + d^5 \sum_{2\leq i\leq n} f_i/(i(i-1))\right).$$

If the points are in convex position, then time

$$O\left(\min\left\{n, \left(d + d^2 \sum_{i\leq n} f_i/(i\cdot n)\right)\log\log n\right\} + d^4 \sum_{i\leq n} f_i/(i\cdot n)\right)$$

suffices.

Proof: This follows immediately from Lemmas 14, the paragraph following this Lemma, and Lemma 18 and 21. ∎

We have $f_i = O(i^{\lfloor d/2 \rfloor})$. A deletion from a convex hull in $\mathbb{R}^3$ therefore takes time $O(\log n)$ and a deletion from a Voronoi diagram in $\mathbb{R}^2$ takes time $O(\log\log n)$. For $d \geq 4$, a deletion from a convex hull in $\mathbb{R}^d$ and a Voronoi diagram in $\mathbb{R}^{d-1}$ takes time $O(n^{\lfloor d/2 \rfloor - 1})$. We note also that for many natural probability distributions, the expected complexity of the hull of random points satisfies $f_r = O(r)$ for fixed d. For such point sets, a random deletion requires $O(\log n)$ expected time.

4 A Tail Estimate for the Size of the History

In this section, we derive a tail estimate for the size of the history. We first prove a general lemma and then apply one of its consequences to obtain a tail estimate for the size of the history in randomized incremental constructions.

In the notation of §2, we want to study the random variable $X = \sum_j deg(y_j, R_j)$ for random permutations $\pi = (y_1, \ldots, y_n)$ of S, inducing the subsets $R_j = \{y_1, \ldots, y_j\}$. Let $p(x) = p_S(x)$ be the generating function of this random variable X, i.e. $p(x) = \sum_{i\geq 0} \Pr[X = i]x^i$. By the following standard observation, we can use bounds on $p(x)$ to show that X is large only with low probability.

Fact 23 *If Z is a non–negative integer random variable with generating function $p(x)$, then for any $k \geq 0$*

$$\Pr[Z \geq k] \leq p(a)/a^k \qquad \textit{for any } a \geq 1.$$

Suppose for some function $M(r)$ we have $b \cdot |\mathcal{F}_0(R)| \leq M(r)$ when $|R| = r$. Then we have the following bound on $p(x)$.

Lemma 19 *Let y be a non-vertex and let O be defined as above. The walk along $\overline{Oy}$ traverses only newly constructed simplices whose base facet is y–visible. The time for the walk is $O(d^2)$ times the number of new simplices with y-visible base facet.*

Proof: The line segment $\overline{Oy}$ is contained in the simplex S. This implies that $\overline{Oy}$ traverses only new simplices. Let S' with base facet G be a simplex traversed. Then G is x–visible. Since S' is intersected by $\overline{Oy}$ and G is visible from every point in S', G must be visible from either O or y. But O-visibility and x-visibility of G and the fact that $y \in \overline{Ox}$ implies y-visibility of G. Thus G is y-visible. The time bound is obvious ∎

At this point we have found one y-visible facet in B.

Lemma 20 *Let $y = x_k$ be a non-vertex. Then all y-visible facets of* $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ *are also x_i-visible.*

Proof: Assume that there are y-visible facets of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ and let F be one of them. Then $x_i \notin \mathrm{conv}\, R_{k-1}$ and there is a facet G of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ such that $y \in S(G, x_i)$. Then the hyperplane supported by F separates G and y. Thus x_i sees F. ∎

The set of y-visible facets of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ is neighbor-connected and is identical to the set of y-visible facets in B. Thus a graph search on B finds all y-visible facets in B in time $O(d^2)$ times their number. The informations (A), (B), and (C) can now be updated as described for the case where y is a vertex. This completes the discussion of the case that x_k is a non-vertex.

Lemma 21 *If x_k is a non-vertex then reinsertion of x_k takes time $O(d^2)$ times the number of new simplices with x_k-visible base facet plus the number of new simplices with peak x_k. The expected total time to reinsert non-vertices is $O(d^4 \sum_{i \le n} f_i/(i \cdot n) + d^5 \sum_{2 \le i \le n} f_i/(i(i-1)))$.*

Proof: The first part follows from Lemmas 19 and 20. For the second part observe that an x_k-visible base facet of a new simplex is either a facet of $\mathrm{conv}\, R_{i-1}$ visible to x_i and x_k or a newly constructed base facet visible to x_i and x_k. The expected number of the first kind of facet is $(E[|G|] - E[|H|] + f_n)/n$ according to Lemma 9 and the expected number of the second kind of facet is $E[|G(\pi \backslash i) \backslash G(\pi)|]$. The bound now follows from Theorems 3 and 8 and Lemma 2. ∎

We can now state the main result of this section.

ensures that all facets and ridges that are in $\mathcal{G}_x$ and in $\mathcal{G}_y$ can be reached from some ridge in $\{f(S); S \in \mathcal{S}(y)\}$. The time bound is obvious. ∎

We next discuss how to update informations (A), (B), and (C). For each x_k-visible facet F of B_{k-1} we construct a new simplex $S = S(F, x_k)$ with peak x_k. The neighbor of S opposite to x_k is the simplex incident to F in (the old) T. Consider any vertex q of S different from x_k next. Then $F = \text{conv}(f \cup \{q\})$ for some ridge f of B. If two facets in B are incident to f then let G be the other facet in B incident to f. If G is x_k-visible then $S(G, x_k)$ is the neighbor of S opposite to q. If G is not x_k-visible then $\text{conv}(f \cup \{x_k\})$ is a facet of $\text{conv}(R_k \setminus \{x_i\})$ and there is no neighbor yet. Assume next that there is only one facet in B incident to f. If $\text{conv}(f \cup \{x_k\})$ is x_i-visible then $\text{conv}(f \cup \{x_k\})$ is a facet of $\text{conv}(R_k \setminus \{x_i\})$ and there is no neighbor yet. Finally, if $\text{conv}(f \cup \{x_k\})$ is not x_i-visible then $f = f(S')$ for some simplex $S' \in \mathcal{S}(x_k)$ and the neighbor of S opposite to q is the neighbor of S' in $T(\pi)$ opposite to x_i. All of this shows that (A) can be updated in time $O(d)$ times the number of new simplices with peak y. We turn to (B) next. Let $B' = B_k$. Lemma 16 describes how to obtain B' from B. The neighborhood relation on B' can be established as follows: On $(B \cap B') \times (B \cap B')$ nothing changes and all new relations can be detected by storing the ridges of the facets in $B' \setminus B$ in the dictionary (C). This takes time $O(d)$ per ridge and hence $O(d^2)$ per facet. Finally, the face equation of each facet in $B' \setminus B$ can be determined in time $O(d^2)$. In summary, informations (A), (B), and (C) can be updated in time $O(d^2)$ times the number of removed and new simplices with peak x_k. This completes the discussion of the case that x_k is a vertex.

Lemma 18 *If x_k is a vertex then reinsertion of x_k takes time $O(d^2)$ times the number of removed and new simplices with peak x_k. The expected total time to reinsert vertices is $O(d^4 \sum_{i \leq n} f_i/(i \cdot n))$.*

Proof: This follows from the discussion above and Lemma 12. ∎

We now turn to the case that $y = x_k$ is a non-vertex, cf. Figure 6, part (b). We first show how to identify a single facet in B visible from y and then argue that a graph search determines all y-visible facets in B. Assume first that y is contained in a simplex $S \in \mathcal{S}(x)$. Let $S = S(F, x)$ and let O be the intersection of F with the line through x and y. Locate y by a walk along $\overline{Oy}$ starting at O. Assume next that y is contained in a simplex $S \in \mathcal{S}(z)$ for some $z \in R(x)$. The ridge $f(S)$ of S with all vertices but x and y is a ridge of B when point z is reinserted and hence the facet spanned by $f(S)$ and z is added to T when point z is reinserted. Let O be the intersection of that facet with the line through x and y. Locate y by a walk along $\overline{Oy}$ starting at O.

Figure 6: This figure illustrates the reinsertion process. Part (a) shows the triangulation before the reinsertion of 9 and Part (b) shows the triangulation before the reinsertion of 10. The set B is shown bold in both cases. The search for the 9-visible facets of B starts at ridge conv($\{8\}$); the search for the 10-visible facets of B starts with a walk along segment $\overline{O\ 10}$ shown dashed in part (b).

(A) a triangulation T which consists of $T(x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_{k-1})$ and the simplices in $T(\pi) \cap T(\pi \backslash i)$,

(B) the set $B = B_{k-1}$, its neighborhood graph, and for each facet $F \in B$ the simplex in T incident to F and the equation of the hyperplane supporting F,

(C) a dictionary for the set of ridges in B.

For the dictionary we use the node labels introduced above (immediately after the proof of Lemma 14) and identify a ridge with the ordered $(d-1)$–tuple of its vertices, i.e., a ridge corresponds to an ordered $(d-1)$–tuple of integers. These tuples are stored in a Trie of depth $d-1$, cf. [Meh84, section III.1.1], whose nodes are realized by dynamic perfect hashing [DKM$^+$88]. In this way all dictionary operations take randomized time $O(d)$ and the space requirement is linear.

The information above is readily initialized ($k = i+1$). T is set to $T(\pi)$ minus the simplices having x_i as a vertex, B is initialized to the set of base facets of simplices in $\mathcal{S}(x_i)$ (neighborhood graph and the association to the simplices in T are induced by $T(\pi)$), and the dictionary is initialized with the set of ridges in B. All of this takes time $O(d^2)$ times the number of removed simplices.

To find the set of x_k-visible facets in B_{k-1} we distinguish cases. Let $y = x_k$ and assume first that y is a vertex, cf. Figure 6, part (a).

Lemma 17 *Let y be a vertex. Then all y-visible facets of B can be reached from a ridge in $\{f(S); S \in \mathcal{S}(y)\}$ in the neighborhood graph of B. The time to find the y-visible facets in B is $O(d)$ times the number of removed and new simplices with peak y.*

Proof: Let $\mathcal{G}$ be the facet graph of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ and let $\mathcal{G}_x$ and $\mathcal{G}_y$ be the parts of $\mathcal{G}$ formed by the facets and ridges of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ that are visible from x and y, respectively. Note that $\mathcal{G}_x$ as well as $\mathcal{G}_y$ is connected (in the topological sense and in the graph theoretic sense). Moreover note that $\mathcal{G}_x$ is nothing but B. The set $\{f(S); S \in \mathcal{S}(y)\}$ comprises exactly all ridges in $\mathcal{G}_y$ for which exactly one of the containing facets is in $\mathcal{G}_x$. Connectedness of $\mathcal{G}_y$ now

of F)
or B contains no x_k-visible facet incident to f and $f = f(S)$ for some $S \in \mathcal{S}(x_k)$.

Figure 5 illustrates this lemma.

Figure 5: An illustration of the two cases of part (b) of Lemma 16. The set B, i.e., the x_i-visible facets of conv R_{k-1} are shown bold.

Proof:

(a) Let $F \in B$. Then $F \in B'$ iff F is not x_k-visible.

(b) Let $F \in B' \setminus B$. Then F is an x_i-visible facet of $\text{conv}(R_k \setminus \{x_i\})$ but not a facet of $\text{conv}(R_{k-1} \setminus \{x_i\})$. Thus $F = \text{conv}(f \cup \{x_k\})$ for some horizon ridge of $\text{conv}(R_{k-1} \setminus \{x_i\})$. Since F is x_i-visible, f is x_i-visible and hence f is a ridge of B. This shows (1). Let G be the unique x_k-visible facet of $\text{conv}(R_{k-1} \setminus \{x_i\})$ incident to f. If $G \in B$ then the first alternative of (2) applies. If $G \notin B$ the $\text{conv}(f \cup \{x_i\})$ is a facet of conv R_{k-1} and hence $S(\text{conv}(f \cup \{x_i\}), x_k)$ is a simplex of $T(\pi)$. Thus $f = f(S)$ for some simplex $S \in \mathcal{S}(x_k)$ and the second alternative of (2) applies.

Assume conversely that F satisfies (1) and (2). The $F = \text{conv}(f \cup \{x_k\})$ for some ridge f of B. Let G and G' be the two facets of $\text{conv}(R_{k-1} \setminus \{x_i\})$ incident to f. By property (2) f is x_k-visible and hence at least one of G and G' is x_k-visible, say G. By property (1) at least one of G and G' belongs to B. We now distinguish cases.

Assume first that $G \in B$. Then the first alternative of (2) applies and therefore $F \in B' \setminus B$ if f is a horizon ridge of $\text{conv}(R_{k-1} \setminus \{x_i\})$. Assume otherwise, i.e., G' is also x_k-visible. Then $G' \notin B$ and hence x_i and G lie in the same halfspace with respect to F (to see this, project into the plane orthogonal to f) and hence F is not x_i-visible, a contradiction to (2).

Assume next that $G \notin B$. Then $G' \in B$ and the second alternative of (2) applies. Since G' is not x_k-visible, F is a facet of $\text{conv}(R_k \setminus \{x_i\})$, and since $\text{conv}(f \cup \{x_i, x_k\})$ is a simplex of $T(\pi)$, F is x_i-visible. Thus $F \in B' \setminus B$.

∎

For $k \geq i$, let B_k be the set of x_i-visible facets of $\text{conv}(R_k \setminus \{x_i\})$. The previous lemma describes how B_k can be obtained from B_{k-1} once the set of x_k-visible facets in B_{k-1} is known. We discuss next how to determine this set. Assume inductively, that the following information is available:

∎

In order to support the efficient computation of the set $R(x)$ we need to augment our data structure slightly. We assume that each point stores a pointer to some simplex containing it and that every simplex stores a list of the points contained in it. We also assume that every point in X carries a label in $[1\,..\,2|X|]$ and that these labels reflect the insertion order. After an insertion the smallest legal label is given to the new point. After a deletion, it may be necessary to relabel the points. If so, label the points with the integers 1 to $|X|$. In this way, the amortized cost of relabeling is $O(1)$.

To determine $R(x)$, check first whether x is a vertex of the simplex pointed to by x. If not, x is removed and we are done. If so, construct the set $R(x)$ by inspection of all simplices incident to x. This takes time proportional to d times $|R(x)|$ plus the number of removed simplices. Sorting the points in $R(x)$ by the time of insertion takes time $O(\min\{n, |R(x)| \log\log n\})$, where the former bound is obtained by bucket sort and the latter bound comes from the use of bounded ordered dictionaries ([vKZ77, MN90]). Note that we can use the label defined above as the keys in the sorting process.

Lemma 11 shows that the x_i-visible facets of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ play an important role in the reinsertion process. The next two emmas characterize the set of these facets. We need the following additional notation. For each point $y \in \{x\} \cup R(x)$ let $\mathcal{S}(y)$ be the set of simplices with peak y and also having x as a vertex. Also for $y \in R(x)$ and for each simplex $S \in \mathcal{S}(y)$ let $f(S)$ be the ridge with all the vertices of S but x and y. The sets $\mathcal{S}(y)$, $y \in R(x)$, can be determined in total time $O(d)$ times the number of removed simplices.

Lemma 15 *A facet F of $\mathrm{conv}\, R_{i-1}$ is x_i-visible iff F is the base facet of a simplex $S \in \mathcal{S}(x_i)$.*

Proof: Obvious. ∎

Lemma 16 *Let $k > i$, let B be the set of x_i-visible facets of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$, and let B' be the set of x_i-visible facets of $\mathrm{conv}(R_k \setminus \{x_i\})$. Then $B' = (B' \cap B) \cup (B' \setminus B)$ and*

(a) *$B' \cap B = B \setminus \{F \in B; F \text{ is not } x_k - \text{visible}\}$.*

(b) *$F \in B' \setminus B$ iff the following two conditions hold:*

- **(1)** *$F = \mathrm{conv}(f \cup \{x_k\})$ for some ridge f of B.*
- **(2)** *either B contains exactly one x_k-visible facet, say G, incident to f and F is x_i-visible (F is a non-base facet of the new simplex $S(G, x_k)$ in this situation and F is x_i-visible iff x_i and G lie on different sides*

and the expected number of new simplices is no larger.

Proof: The expected number of simplices in $T(\pi)$ with peak $\overline{O}$ is f_n and the expected number of simplices in $T(\pi)$ with peak different from $\overline{O}$ is $C_n - f_n$ according to Theorem 10. The corresponding numbers for $T(\pi\backslash i)$ are f_{n-1} and $C_{n-1} - f_{n-1}$ according to Theorem 10 and Lemma 1. Also each simplex of $T(\pi)$ has $d+1$ vertices and therefore the expected number of removed simplices is $(d+1)(C_n - f_n)/n + df_n/n = (d+1)C_n/n - f_n/n$. The expected number of new simplices is thus $C_{n-1} - (C_n - (d+1)C_n/n + f_n/n)$ which is no larger than the number of removed simplices. The bound now follows from Theorem 3 and Lemma 2. ∎

The next lemma restricts the set of k for which there may be an x_i- and x_k-visible facet of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$.

Lemma 13 *If there is an x_i- and x_k-visible facet of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$ then $x_k \in R(x_i)$.*

Proof: Let $x = x_i$, $y = x_k$ and let F be an x_i- and x_k-visible facet of $\mathrm{conv}(R_{k-1} \setminus \{x\})$. The hyperplane supporting F separates $\mathrm{conv}(R_{k-1} \setminus \{x\})$ from y and x and hence y is not the convex combination of points in $R_{k-1} \setminus \{x\}$. We now distinguish cases. If $y \in \mathrm{conv}\, R_{k-1}$ then y is the convex combination of points in R_{k-1} and therefore the simplex of T containing y must have x as a vertex. Thus $y \in R(x)$. If $y \notin \mathrm{conv}\, R_{k-1}$ then some facet G of $\mathrm{conv}\, R_{k-1}$ that contains x must be visible from y (e.g. one that intersects the line segment joining y with some point of F, which, being visible from x, is not a facet of $\mathrm{conv}\, R_{k-1}$). But now $S(G, y)$ is a simplex of T, and hence $y \in R(x)$. ∎

Lemma 14 *The expected size of $R(x)$ is bounded by*

$$(d+1)\left(2 + d\sum_{i \le n} f_i/(i \cdot n)\right).$$

Proof: Let $R_1(x)$ be the set of points $y \in R(x)$ which are vertices of $T(\pi)$ and let $R_2(x) = R(x) \setminus R_1(x)$. To bound $|R_1(x)|$, observe that $|R_1(x)|$ is at most d plus the number of destroyed simplices. Thus

$$E\left[|R_1(x)|\right] \le d + \sum_{i \le n} d(d+1)f_i/(i \cdot n).$$

To bound $|R_2(x)|$, observe that each non–vertex y is incident to exactly one simplex (recall that our points are in general position) and that x is the vertex of such a simplex with probability $(d+1)/n$. Thus

$$E\left[|R_2(x)|\right] \le n(d+1)/n = (d+1).$$

Figure 4: The triangulation $T(\pi\backslash\{5\})$. The simplices in $T(\pi\backslash\{5\})\backslash T(\pi)$ are shown hatched. The set $R(5)$ consists of points 6, 8, 9, 10, and $\overline{O}$.

also inserted after x. We will, in effect, reinsert the points of $R(x)$ in the order in which they were inserted into R, constructing only those simplices that have bases visible to x. On a superficial level, this describes the deletion process. The details follow.

Let $\pi = (x_1, \ldots, x_n)$ be the insertion order and assume that $x = x_i$ is deleted. We assume that x_i is a vertex of $T(\pi)$ because otherwise the deletion is trivial. We first characterize the triangulation $T(\pi \setminus i)$, cf. Figure 4 for an example. Recall that we use $\mathrm{vertex}(F)$ to denote the set of vertices of a face F.

Lemma 11 **(a)** *Let $S(F, x_j)$ be a simplex of $T(\pi)$. Then $S(F, x_j)$ is a simplex of $T(\pi\backslash i)$ iff $x_i \notin \mathrm{vertex}(F) \cup \{x_j\}$.*

(b) *$S(F, x_k)$ is a simplex of $T(\pi\backslash i)$ which is not already a simplex of $T(\pi)$ iff $k > i$ and F is an x_i- and x_k-visible facet of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$.*

Proof:

(a) Let $S = S(F, x_j)$. Clearly, if $x_i \in \mathrm{vertex}(F) \cup \{x_j\}$ then S is not a simplex of $T(\pi\backslash i)$. So assume that S is simplex of $T(\pi)$ and that $x_i \notin \mathrm{vertex}(F) \cup \{x_j\}$. Then F is a facet of $\mathrm{conv}\, R_{j-1}$ and since $x_i \notin \mathrm{vertex}(F)$ also a facet of $\mathrm{conv}(R_{j-1}\backslash\{x_i\})$. Since $i \neq j$ this implies that S is a simplex of $T(\pi\backslash i)$.

(b) Let $S(F, x_k)$ be a simplex of $T(\pi\backslash i)$ which is not already a simplex of $T(\pi)$. Then $k > i$ and F is an x_k-visible facet of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$. If F were not x_i-visible then F were also a facet of $\mathrm{conv}\, R_{k-1}$ and hence $S(F, x_k)$ a simplex of $T(\pi)$.

Assume conversely that $k > i$ and that F is an x_i- and x_k-visible facet of $\mathrm{conv}(R_{k-1} \setminus \{x_i\})$. Then $S(F, x_k)$ is clearly a simplex of $T(\pi\backslash i)$. Also, F is not a facet of $\mathrm{conv}\, R_{k-1}$ and hence $S(F, x_k)$ is not a simplex of $T(\pi)$.

∎

Having characterized the set of simplices to be removed and to be constructed we next estimate their number under the assumption that the points were inserted in random order and that a random point is deleted.

Lemma 12 *The expected number of removed simplices is bounded by*

$$\sum_{i \leq n} d(d+1) f_i / (i \cdot n)$$

(c) *The expected time to construct the convex hull of n points using either search method is*

$$O(d^3)\sum_j \frac{d}{j} f_j + O(d^3)\sum_j \frac{d(d-1)}{j(j-1)}(n-j+1)f_j = O(d^5)\sum_j \frac{nf_j}{j(j-1)}.$$

Proof:

(a) Each simplex has a base facet, and so the bound follows from Theorem 3 and Lemma 2.

(b) From the above discussion, we need to find $E[t_1]$, the expected number of facets that are x_r–visible. The expected number of visible facets is $-c_r + \sum_{j \le r} p_j$, by Theorem 4.

(c) We argued above that the time needed to update the triangulation after the insertion of x is $O(d^3)(t_3 + t_4)$, where t_3 is the number of simplices with peak x and t_4 is the number of new simplices with peak $\overline{O}$. Thus every simplex of T_n contributes to the update cost at most twice. Once when it is created with peak $\overline{O}$ and once when its peak is altered to a point in X. The bound follows, using (a) and summing the bound of (b) over r, with renaming the index r to j and resolving the double sum of the second term.

∎

Since $f_r = O(r^{\lfloor d/2 \rfloor})$ in the worst case, the running time is $O(n \log n)$ for $d \le 3$, and $O(n^{\lfloor d/2 \rfloor})$ for $d \ge 4$. We note also that for many natural probability distributions, the expected complexity of the hull of random points satisfies $f_r = O(r)$ for fixed d. For such point sets, our algorithm requires $O(n \log n)$ expected time.

3.3 The Deletion Algorithm and its Analysis

The global plan is quite simple. When a point x is deleted from R, we change the triangulation T so that in effect x was never added. This is in the spirit of § 2, which in the last few theorems analyzes the effect of the omission of an element from a permutation on the sizes of the associated history and conflict history structures.

The effect of the deletion of x on the triangulation T is easy to describe. All simplices having x as a vertex disappear (If x is not a vertex of T then T does not change). The new simplices of T resulting from the deletion of x all have base facets visible to x, with peak vertices inserted after x. These are the simplices that would have been included had x not been inserted into R. Let $R(x)$ be the set of points of R that are contained in simplices with vertex x, and

In the segment-walking method the time spent on the walk is $O(d^2) \cdot t_0$, since given the entry point of segment $\overline{Ox}$ into a simplex S the exit point can be found in time $O(d^2)$; it takes time $O(d)$ per facet to compute the point of intersection, i.e., $O(d^2)$ altogether, and $O(d)$ time to select the first intersection following the entry point. The segment-walk determines the simplex containing x. All visible hull facets can then be determined in time $O(d^2) \cdot t_3$, since visiblity can be checked in time $O(d)$ per base facet and since a visible facet has at most d invisible neighbors. We define the search time of the segment-walking method to be $O(d^2) \cdot t_0 = O(d^2) \cdot t_1$ and include the $O(d^2) \cdot t_3$ term in the update time.

The search time for the all-visibilities method is $O(d) \cdot t_2 = O(d^2) \cdot t_1$, since $O(d)$ per simplex is needed for the visibility check and since the degree of the neighborhood graph is $d+1$.

Let's turn to the update time next. We need to alter t_3 simplices; this takes time $O(1) \cdot t_3$. For each new simplex we have to compute the equation of the hyperplane supporting the base facet. This takes time $O(d^3) \cdot t_4$, since solving the linear systems for the normal vectors requires $O(d^3)$ time per simplex (A factor of d can be removed using complicated rank-one updating techniques, if desired.). Finally, we need to update the neighbor relation. Let $\mathcal{S} = \mathcal{S}_{f,q}$ be defined as in the previous section. The walk through $\mathcal{S}$ takes time $O(d \cdot |\mathcal{S}|)$, since the neighbors in $\mathcal{S}$ of a simplex in $\mathcal{S}$ can be determined in time $O(d)$. Next observe, that a simplex $S = S(F, x) \in \mathcal{V}$ can belong to at most $d(d-1)$ different sets $\mathcal{S}_{f,q}$, since $f \setminus \{q\}$ can be obtained from F by deleting two vertices ($\binom{d}{2}$ choices) and since there are only two choices for q once $f \setminus \{q\}$ is fixed (Note that there are only two horizon ridges containing $f \setminus \{q\}$.). Thus the time to update the neighbor relation is $O(d^3) \cdot t_3$ and total update time is $O(d^3) \cdot (t_3 + t_4)$.

We next establish the connection to § 2. Our regions are halfspaces. More formally, we have $b = d$ and $\mathcal{F}(X)$ contains two copies of each subset $\{x_1, \ldots, x_d\} \subseteq X$ of cardinality d. These two copies are identified with the two open halfspaces defined by the hyperplane through points $x_1, x_2, \ldots, x_d$. A point x is said to conflict with a halfspace if it is contained in the halfspace. In this way, for $|R| \geq d+1$ the regions in $\mathcal{F}_0(R)$ correspond precisely to the facets of the convex hull of R (recall that we assume our points to be in general position) and a facet F of $\operatorname{conv} R$ is visible from $x \notin R$ if x conflicts with the halfspace supporting the facet. Also $|\mathcal{F}_0(R)| = 2$ if $|R| = d$, $\mathcal{F}_0(R) = \emptyset$ for $|R| < d$, and $\mathcal{F}(X)$ is uniform. Using the notation of §2, we therefore have $f_r = 0$ for $r < d$ and $f_d = 2$; for $r > d$, f_r is the expected number of facets of $\operatorname{conv} R$ for random subset $R \subseteq X$ with $|R| = r$.

Theorem 10 (a) *The expected number of simplices of T_r is $C_r = \sum_{j \leq r} df_j/j$.*

(b) *The expected search time for x_r, using either search method, is $O(d^2)$ times*

$$-c_r + \sum_{2 \leq j \leq r} p_j = -\frac{d}{r} f_r + \sum_{2 \leq j \leq r} \frac{d(d-1)}{j(j-1)} f_j.$$

$\mathrm{conv}(f \cup \{\overline{O}\})$; $\overline{V} \in \mathcal{V}$ and $N \notin \mathcal{V}$. In the updated triangulation $\overline{V}$ is replaced by a new simplex V that has the same base but peak x. The neighbor of A_f opposite to x is N and the neighbor opposite to $\overline{O}$ is V. Now consider any vertex $q \in f$ and let $\mathcal{S} = \mathcal{S}_{f,q}$ be the set of simplices with peak x and including $\mathrm{vertex}(f) \setminus \{q\} \cup \{x\}$ in their vertex set; for a face f we use $\mathrm{vertex}(f)$ to denote the set of vertices contained in f. We will show that the neighbor of A_f opposite to q can be determined by a simple walk through $\mathcal{S}$. This walk amounts to a rotation about the $(d-2)$–face $\mathrm{conv}(\mathrm{vertex}(f) \setminus \{q\} \cup \{x\})$. Note first that $V \in \mathcal{S}$. Consider next any simplex $S = S(F, x) \in \mathcal{S}$. Then $F = \mathrm{conv}(f \setminus \{q\} \cup \{y_1, y_2\})$ for some vertices y_1 and y_2. Thus S has at most two neighbors in $\mathcal{S}$, namely the neighbors opposite to y_1 and y_2 respectively. Also, V has at most one neighbor in $\mathcal{S}$, namely the neighbor opposite to q (Note that the neighbor opposite to y, where $\mathrm{conv}(f \cup \{y\})$ is the base facet of V, is the simplex $A_f \notin \mathcal{S}$.). The neighbor relation thus induces a path on the set $\mathcal{S}$ with V being one end of the path. Let V' with base facet $\mathrm{conv}(f \setminus \{q\} \cup \{y_1, y_2\})$ be the other end of the path. Assume that the neighbor of V' opposite to y_1, call it B, does not belong to $\mathcal{S}$ and that $y_1 = q$ if $V = V'$, i.e., the path has length zero. The simplex B includes $\mathrm{vertex}(f) \setminus \{q\} \cup \{y_2, x\}$ in its vertex set and does not have peak x. Thus B has peak $\overline{O}$ and hence B is the neighbor of A_f opposite to q. This completes the description of the update step. Figure 3 illustrates the update step.

Figure 3: f is a horizon ridge, x a new vertex, and q a vertex of f. In the updated triangulation the simplices A_f and N are incident to the facet $\mathrm{conv}(f \cup \{\overline{O}\})$ and the simplices V and A_f are incident to the facet $\mathrm{conv}(f \cup \{x\})$. $\mathcal{S}$ is the set of simplices with peak x and incident to the ridge $\mathrm{conv}(\{p, x\})$. The base facets of these simplices are $\mathrm{conv}(\{p, y, y'\})$, $\mathrm{conv}(\{p, y', y''\})$, $\mathrm{conv}(\{p, y'', y_1\})$, $\mathrm{conv}(\{p, y_1, y_2\})$. The walk through $\mathcal{S}$ ends in simplex $\mathrm{conv}(\{p, y_1, y_2, x\})$.

3.2 Analysis of Insertions

The cost of adding a point to set R is the time needed to locate the point x in the triangulation T, plus the time needed to update the triangulation.

We need some additional notation. Let t_0 be the number of simplices visited by the walk along segment $\overline{Ox}$, let t_1 be the number of simplices with x-visible base facet, let t_2 be the number of simplices visited by the all-visibilites method, let t_3 be the number of simplices with peak x, and let t_4 be the number of new hull facets. Then $t_0 \leq t_1$, since the base facets of all simplices traversed by the segment-walking method see x, and $t_2 \leq (d+1) \cdot t_1$ since a simplex has $d+1$ neighbors.

Two simplices of T are *neighbors* if they share a facet. The neighbor relation defines the neighborhood graph on the set of simplices. Call a neighbor of some simplex S and a vertex x of S *opposite to each other*, if the common facet does not contain x. In an implementation, we propose to store the directed version of the neighborhood graph augmented by information which supports the following operations in constant time: identification of the neighbor of a simplex sharing the base facet, identification of the peak vertex of a simplex, and identification of the vertex opposite to a facet. We also store or each simplex the equation of the hyperplane supporting the base facet of the simplex. The equation is normalized such that the peak lies in the positive halfspace.

We discuss next two *search* methods for finding the x-visible current facets of $\operatorname{conv} R$. The first method seems easier to implement, the second method is easier to analyse.

Here is one method: locate x in T by walking along the segment $\overline{Ox}$ beginning at O. If this walk enters a simplex whose peak vertex is the anti-origin, then an x-visible current facet has been found. Otherwise, a simplex of T containing x has been found, showing that $x \in \operatorname{conv} R$. In the former case, find all x-visible hull facets by a search of the simplices incident to the anti-origin. These simplices form a connected set in the neighborhood graph. We call this search method the *segment-walking* method.

Another search method is the following: starting at the origin simplex and the simplex sharing its base facet explore simplices according to the rule: if a simplex has an x-visible base facet, search its neighbors (not including the neighbor that shares the base facet). Here we say that a base facet F is x-visible if that was true (in the previous sense) at the time that F was a current hull facet. This search procedure reaches all x-visible current hull facets, i.e., all simplices $S(F, \overline{O})$ with x-visible base facet F, since the base facets of all simplices traversed in the segment-walking search method are x-visible. We call this search scheme the *all-visibilities* method.

We finally turn to the update procedure. At this point, we have found the current hull facets seeing x, in the form of the simplices whose base facets see x and with the anti-origin as their peak vertex. Let $\mathcal{V}$ be the set of such simplices. Now we update T by altering these simplices, and creating some others. The alteration is simply to replace the anti-origin with x in every simplex in $\mathcal{V}$.

The new simplices correspond to new hull facets. Such facets are the hull of x and a horizon ridge f; a *horizon ridge* is a $(d-2)$–dimensional face of $\operatorname{conv} R$ with the property that exactly one of the two incident hull facets sees x. Each horizon ridge f gives rise to a new simplex A_f with base facet $\operatorname{conv}(f \cup \{x\})$ and peak $\overline{O}$. For each horizon ridge of $\operatorname{conv} R$ there is a non-base facet G of a simplex in $\mathcal{V}$ such that x does not see the base facet of the other simplex incident to the facet G. Thus the set of horizon ridges is easily determined.

It remains to update the neighbor relationship. Let $A_f = S(\operatorname{conv}(f \cup \{x\}), \overline{O})$ be a new simplex corresponding to horizon ridge f. In the old triangulation (before adding x) there were two simplices $\overline{V}$ and N incident to the facet

denote the convex hull of R. We let $x_1, x_2, \ldots, x_n$ denote the points in X in the order of their insertion, and let R_i denote $\{x_1, \ldots, x_i\}$.

3.1 The Insertion Algorithm

To maintain the convex hull of R under insertions, we maintain a triangulation T of the hull: a simplicial complex whose union is conv R. (A simplicial complex is a collection of simplices such that the intersection of any two is a face of each.) The vertices of the simplices of T are points of R. The triangulation is updated as follows when a point x is added to R: if $x \in \operatorname{conv} R$, and so is in some simplex S of T, leave T as it was. If $x \notin \operatorname{conv} R$, then for every facet F of the hull of R visible to x, add to T the simplex $S(F, x) = \operatorname{conv}(F \cup \{x\})$. Call F the *base* facet and x the *peak* vertex of the simplex. A facet is *visible* to x or *x-visible* just when $S(F, x)$ meets the hull only at F. We may also say, for x-visible F, that x is visible to F, and they *see* each other. Use T_r to denote the triangulation after the insertion of $x_1, x_2, \ldots, x_r$.

This process is called triangulation by "placing" [Ede87]. It should be clear that the stated conditions on the triangulation are preserved. (When $r \leq d+1$, we simply maintain a single $(r-1)$–dimensional simplex.) It will be convenient to extend the triangulation so that facets of the current hull are also base facets of simplices; this gives a uniform representation. The peak vertex of these simplices is a "dummy" that in effect is visible to all current facets; we use $\overline{O}$ to denote this dummy vertex and we use O to denote a point inside the first full-dimensional simplex created, when $r = d+1$. (Here we use the assumption of nondegenerate position.) Call the first full-dimensional simplex the *origin simplex.* Adopting the terminology of "two-sided space" of Stolfi [Sto87] we call O and $\overline{O}$ the origin and anti-origin respectively: while the origin sees no facets of the current hull of R, the anti-origin sees all of them. We use T to also denote the extended triangulation. To carry the uniformity even further, we designate the vertex x_{d+1} the peak of the origin simplex and call its opposite facet the base of the origin simplex. In this way, there are $d+2$ simplices in the (extended) triangulation when the first full-dimensional simplex is created: the origin simplex and $d+1$ simplices with peak $\overline{O}$. One facet of the origin simplex (better: its two sides) is base facet of two simplices and all other facets of the origin simplex are base facet of one simplex. Figure 2 shows an extended triangulation.

Figure 2: An extended triangulation. The points are numbered according to insertion time. All unbounded edges have their other endpoint at $\overline{O}$. The dashed line segment indicates the walk along segment $\overline{O\,10}$. The simplices with 10–visible based facet are shaded. Figure 1 shows the base facets of all simplices.

(Alternatively, note that $E[|G|] - E[|G(\pi\backslash i)|]$ is the expected number of regions of H_n conflicting with x_i, and use Theorem 4.) We need to find $E[|G\backslash G(\pi\backslash i)|]$. A pair (x, F) is in $G\backslash G(\pi\backslash i)$ if it is in G and either $x_i = x$ or $x_i \in F$. At most $b+1$ choices of x_i allow this, for any $(x, F) \in G$, and so $E[|G\backslash G(\pi\backslash i)|] \leq (b+1)E[|G|]/n$, with equality if $\mathcal{F}(S)$ is uniform. The result follows using Theorem 6 and easy manipulations. ∎

In the convex hull algorithm of §3, the conflicts of $G(\pi\backslash i)\backslash G(\pi)$ are not quite all those examined when deleting x_i. The following bound will also be useful.

Lemma 9 *For a fixed i let I be the set of conflicts of the form (x_j, F) with $j > i$ and $F \in \mathcal{F}_0(R_{i-1}) \setminus \mathcal{F}_0(R_i)$. Then for random $\pi \in \Pi_S$ and random $i \in [1\,..\,n]$, $E[|I|] = (E[|G|] - E[|H|] + f_n)/n$.*

Proof: Let I_i denote the set I for x_i. Then $E[|I|] = \sum_i E[|I_i|]/n$, and since the I_i are disjoint, $E[|I|] = E[|\cup_i I_i|]/n$. For any conflict $(x_j, F) \in G$, either $F \in \mathcal{F}_0(R_{j-1})$, or there is exactly one $i < j$ such that $F \in \mathcal{F}_0(R_{i-1})\backslash\mathcal{F}_0(R_i)$. In the latter case, $(x_j, F) \in I_i$. To count the conflicts (x_j, F) with $F \in \mathcal{F}_0(R_{j-1})$, note that each $F \in H\backslash\mathcal{F}_0(S)$ appears this way exactly once. Thus $E[|G|] = E[|\cup_i I_i|] + E[|H|] - |\mathcal{F}_0(S)|$, from which the Lemma follows. ∎

In our example, the set I_i contains all conflicts (x_j, F) where $j > i$ and F is a hull facet of conv R_{i-1} but not of conv R_i, i.e., F is an x_i– and x_j–visible facet of conv R_{i-1}.

3 Dynamic Convex Hulls

We apply the results of §2 to the problem of maintaining the convex hull in d-dimensional space under insertions and deletions of points. Recently a number of similar results have appeared. They differ from our results as follows. Schwarzkopf [Sch91, Sch92] achieves comparable or slightly weaker bounds (except for expected constant time deletions for 3-dimensional point sets in convex position). He uses an extensive history structure that also maintains past deletions. In contrast, our method makes deleted points completely disappear from our history structure. Mulmuley [Mul91c, Mul91a, Mul91b] achieves bounds similar to Schwarzkopf. He does not maintain a structure that represents the history of insertions in their true order, but rather in a fictitious random order. Finally, Devillers, Teillaud et al. use methods and achieve bounds very similar to ours. In [BDS+] they only consider insertions. In [DMT91] they consider insertions and deletions, but only for 2-dimensional Delaunay triangulations.

Let $X \subset \mathbb{R}^d$ be a set of points, which we assume to be in nondegenerate position: no $d+1$ of them lie in a common hyperplane. For $R \subseteq X$, let conv R

Theorem 7

$$\frac{1}{n!n} \sum_{\pi \in \Pi_S} \sum_i |H(\pi) \oplus H(\pi \backslash i)| \leq 2b\frac{C_n}{n} - c_n,$$

with equality if $\mathcal{F}(S)$ is uniform.

Proof: For finite sets A and B,

$$|B \oplus A| = |A| - |B| + 2|B \backslash A|,$$

and so for $H = H(\pi)$ and $H(\pi \backslash r)$,

$$|H \oplus H(\pi \backslash r)| = |H(\pi \backslash r)| - |H| + 2|H \backslash H(\pi \backslash r)|.$$

The set $H \backslash H(\pi \backslash i)$ comprises the regions in H supported by x_i. By Theorem 3, $E[|H|] = C_n$, and any $F \in H$ is supported by no more than b objects, with equality if $\mathcal{F}(S)$ is uniform. Therefore on average the random $x_i \in S$ supports no more than bC_n/n regions of H. By Theorem 3 and Lemma 1, we have $E[|H(\pi \backslash i)|] = C_{n-1}$, and the theorem follows since $C_{n-1} - C_n = -c_n$ by definition. ∎

Theorem 8

$$\begin{aligned} E[|G(\pi \backslash i) \backslash G(\pi)|] &= \frac{1}{n!n} \sum_{\pi \in \Pi_S} \sum_i |G(\pi \backslash i) \backslash G(\pi)| \\ &\leq c_n - (b+1)C_n/n + \sum_j bp_j - \sum_j (b+1)(j-1)p_j/n, \end{aligned}$$

with equality if $\mathcal{F}(S)$ is uniform.

Proof: Letting $G = G(\pi)$, we have

$$|G(\pi \backslash i) \backslash G| = |G(\pi \backslash i)| - |G| + |G \backslash G(\pi \backslash i)|,$$

and by linearity of expectation,

$$E[|G(\pi \backslash i) \backslash G|] = E[|G(\pi \backslash i)|] - E[|G|] + E[|G \backslash G(\pi \backslash i)|].$$

Theorem 6 gives an expression for $E[|G|]$, and together with Lemma 1 it gives a similar expression for $E[|G(\pi \backslash i)|]$, yielding

$$E[|G(\pi \backslash i) \backslash G|] = E[|G \backslash G(\pi \backslash i)|] + c_n - \sum_j p_j.$$

(b) *The expected number of regions in* $\mathcal{F}_0(R_{j-1})$ *supported by* x_{j-1} *and in conflict with* x_r *is at most* $b(f_{j-1} - f_j + c_j)/(j-1)$*, with equality if* $\mathcal{F}(S)$ *is uniform.*

Proof:

(a) For $x \notin R$ the conflict free region sets $\mathcal{F}_0(R)$ and $\mathcal{F}_0(R \cup \{x\})$ differ in two ways: the regions in $\mathcal{F}_0(R)$ that conflict with x have to be removed, the regions in $\mathcal{F}_0(R \cup \{x\})$ that are supported by x have to be added. Thus we have

$$\begin{aligned}\mathcal{F}_0(R_{j-1} \cup \{x_r\}) &= \mathcal{F}_0(R_{j-1}) \backslash \{F \in \mathcal{F}_0(R_{j-1}); (x_r, F) \in C\} \\ &\cup \{F \in \mathcal{F}_0(R_{j-1} \cup \{x_r\}); x_r \text{ supports } F\}\end{aligned}$$

and hence the desired quantity is

$$E[|\mathcal{F}_0(R_{j-1})|] - E[|\mathcal{F}_0(R_{j-1} \cup \{x_r\})|] + E[|\{F \in \mathcal{F}_0(R_{j-1} \cup \{x_r\}); x_r \text{ supports } F\}|]$$
$$= f_{j-1} - f_j + c_j$$

(b) x_{j-1} is a random element of R_{j-1}. Hence a region considered in part (a) is supported by x_{j-1} with probability at most $b/(j-1)$.

∎

Summation of the bound in Lemma 5b for j from 1 to $r-1$ gives an alternative to Theorem 4 for the bound on the expected number of regions in H_{r-1} which conflict with x_r.

The *conflict history* $G = G_n = G(\pi)$ for insertion sequence $\pi = (x_1, \cdots, x_n)$ is the relation $C \cap (S \times H_n)$. We may also describe this relation as a bipartite graph, with an edge between object $x \in S$ and region $F \in H_n$ when x and F conflict. The conflict history corresponds to the union (over time) of the conflict graphs in [CS89]. We use $|G|$ to denote the size of the conflict history, i.e., the number of pairs in it.

Theorem 6 *The expected size of the conflict history is*

$$E[|G|] = -C_n + \sum_j (n-j+1)p_j$$

Proof: Theorem 4 counts the expected number of edges incident to node $x_r \in S$. The claim follows by summation over r. ∎

We next turn to random deletions. For $\pi = (x_1, \ldots, x_n) \in \Pi_S$ and $i \in [1 \,..\, n]$, let

$$\pi \backslash i = (x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n).$$

We bound the expected size of the difference between $H(\pi)$ and $H(\pi \backslash i)$ and between $G(\pi)$ and $G(\pi \backslash i)$ for random $\pi \in \Pi_S$ and random $i \in [1 \,..\, n]$.

triangulation and then actually change the triangulation. In section 3 we will see that the time to locate a new point is proportional to the number of facets in the history visible from the new point. It is clear that, if the new point had been inserted first, then precisely these facets would have never been constructed. This simple geometric observation leads the way to our new analysis of the expected search cost.

Theorem 4 *The expected number of regions in H_{r-1} which are in conflict with x_r is $-c_r + \sum_{j \leq r} p_j$.*

Proof: Let X be the number of regions $F \in H_{r-1}$ with $(x_r, F) \in C$. Let $H = H_{r-1} = H(x_1, \ldots, x_{r-1})$ and $H' = H(x_r, x_1, \ldots, x_{r-1})$, i.e., in H' we "pretend" that x_r was put in first. We have

$$|H| + |H' \setminus H| = |H'| + |H \setminus H'|,$$

which holds for any two finite sets. Now $X = |H \setminus H'|$ since $H \setminus H'$ is the set of regions in H which conflict with x_r. On the other hand, $H' \setminus H$ comprises regions supported by x_r; to count these regions, we count how many of them appear when x_j is inserted. That is, letting $R'_j = R_j \cup \{x_r\}$, for each region $F \in H' \setminus H$ we either have $F \in \mathcal{F}_0(\{x_r\})$ or there is exactly one $j \geq 1$ such that $F \in \mathcal{F}_0(R'_j)$ and x_j supports F. In the latter case the region is also supported by x_r, and so for given j the number of regions we count is $pdeg(x_r, x_j, R'_j)$. Putting these observations together,

$$X = |H| - |H'| + |\mathcal{F}_0(\{x_r\})| + \sum_{1 \leq j \leq r-1} pdeg(x_r, x_j, R'_j),$$

and so

$$E[X] = E[|H|] - E[|H'|] + E[|\mathcal{F}_0(\{x_r\})|] + \sum_{1 \leq j \leq r-1} E[pdeg(x_r, x_j, R'_j)]$$

We have $E[|H|] = C_{r-1}$ by Theorem 3, and $E[|H'|] = C_r$ by Theorem 3 and Lemma 1. Moreover, recall that $C_{r-1} - C_r = -c_r$. Also $E[|\mathcal{F}_0(\{x_r\})|] = f_1 = p_1$ by convention, and $E[pdeg(x_r, x_j, R'_j)] = p_{j+1}$, since $R'_j = R_j \cup \{x_r\}$ is a random subset of S of size $j+1$ and x_r and x_j are random elements of this subset. ∎

The following estimates are also useful.

Lemma 5 *For $j \leq r$ the following holds:*

(a) *The expected number of regions in $\mathcal{F}_0(R_{j-1})$ in conflict with x_r is $f_{j-1} - f_j + c_j$.*

We are now ready for an average case analysis of randomized incremental constructions. All expected values are computed with respect to a random ordering $(x_1, \cdots, x_n) \in \Pi_S$ of the objects in S.

Lemma 2 *The expectations c_r, p_r, and f_r satisfy $c_r \leq bf_r/r$, and for $r > 1$, $p_r \leq b(b-1)f_r/r(r-1)$, with equality if $\mathcal{F}(S)$ is uniform.*

Proof: For every region $F \in \mathcal{F}(S)$ there are at most b objects and at most $b(b-1)$ ordered pairs of objects which support F, and exactly as many if $\mathcal{F}(S)$ is uniform. ∎

Theorem 3 *Let C_r be the expected size of history H_r. Then $C_r = \sum_{j \leq r} c_j$.*

Proof: H_0 is empty and hence $C_0 = 0$. For $r \geq 1$ the number of elements of H_r which are not already elements of H_{r-1} is equal to $deg(x_r, R_r)$. Since R_r is a random subset of S of size r and x_r is a random object in R, we have

$$E[deg(x_r, R_r)] = E[c(R_r)] = c_r.$$

∎

In §4 we will strengthen Theorem 3 and prove a tail estimate for $|H_n|$. Let us give a geometric interpretation of H_r in our example. In section 3 we show how to maintain convex hulls under insertions and deletions. To do so, we maintain a triangulation T of the convex hull: a simplicial complex whose union is conv R. (A simplicial complex is a collection of simplices such that the intersection of any two is a face of each.) The vertices of the simplices of T are points of R. The triangulation is updated as follows when a point x is added to R: if $x \in$ conv R, and so is in some simplex S of T, leave T as it was. If $x \notin$ conv R, then for every facet F of the hull of R visible to x, add to T the simplex $S(F, x) =$ conv $(F \cup \{x\})$. Call F the *base* facet and x the *peak* vertex of the simplex. A facet is *visible* to x or x-*visible* just when $S(F, x)$ meets the hull only at F. Use T_r to denote the triangulation after the insertion of $x_1, x_2, \ldots, x_r$. Then H_r is in one–to–one correspondence with the facets of T_r which were hull facets at some point during the construction, cf. Figure 1.

Figure 1: An triangulation. The points are numbered according to insertion time. The facets counted in the history are shown bold.

Suppose now that we have to update the hull and its triangulation after the insertion of a new point. We will first locate the new point in the current

random subset of S of size j, $(x_1, \ldots, x_j)$ is a random permutation of R_j, x_j is a random element of R_j, and if δ is a (fixed) permutation, then $\pi\delta$ is a random permutation.

For subset $R \subseteq S$, $r = |R|$, and distinct objects $x, y \in R$, let

$$\begin{aligned} deg(x, R) &= |\{F \in \mathcal{F}_0(R); x \text{ supports } F\}| \\ pdeg(x, y, R) &= |\{F \in \mathcal{F}_0(R); x \text{ and } y \text{ support } F\}| \\ c(R) &= \frac{1}{r} \sum_{x \in R} deg(x, R) \\ p(R) &= \frac{1}{r(r-1)} \sum_{(x,y) \in R^2} pdeg(x, y, R) . \end{aligned}$$

We call $deg(x, R)$ the *degree* of x in R, $pdeg(x, y, R)$ the *degree* of the ordered pair (x, y) in R, $c(R)$ the *average degree* of a random object in R and $p(R)$ the *average pair degree* of a random pair of objects in R. Of course, $p(R)$ is only defined for $r \geq 2$.

For a random variable X, we use $E[X]$ or simply EX to denote the expectation of X. For integer r, $1 \leq r \leq n$, let

$$c_r = E[c(R)] = \sum_{R \subseteq S, |R| = r} c(R) / \binom{n}{r}$$

and

$$p_r = E[p(R)] = \sum_{R \subseteq S, |R| = r} p(R) / \binom{n}{r}$$

be the expected average degree and pair degree for random $R_r \subset S$, and let

$$f_r = \sum_{R \subseteq S, |R| = r} |\mathcal{F}_0(R)| / \binom{n}{r}$$

be the expected number of conflict-free regions of $\mathcal{F}(R)$, with respect to random R_r. Note that $c_1 = f_1$. It will be convenient to adopt the convention that $c_j = p_j = f_j = 0$ for $j < 1$ or $j > n$, and (almost always) convenient to adopt the convention that $p_1 = f_1$.

In the following discussion it may be helpful to the reader to keep our example in mind. Here regions $F \in \mathcal{F}(R)$ correspond to facets of the convex hull of R and x conflicts with F corresponds to x being able to "see" that facet. The term $deg(x, R)$ is the number of facets of conv$R$ that contain x and c_r is its expectations. Similarly, $pdeg(x, y, R)$ is the number of facets of conv$R$ containing both x and y, and p_r is its expectation. These expectations are over all x (and y) in R and over all $R \subset S$ of size r. Note that S is fixed once and for all.

Let S be a set with $|S| = n$ elements, which we will sometimes call *objects*. Let $\mathcal{F}(S)$ be a multiset whose elements are nonempty subsets of S, and let b be the size of the largest element of $\mathcal{F}(S)$. We will call the elements of $\mathcal{F}(S)$ *regions* or *ranges*. If all the regions have size b, we will say that $\mathcal{F}(S)$ is *uniform*. For a region $F \in \mathcal{F}(S)$ and an object x, if $x \in F$ we say that F *relies on* x or x *supports* F. For $R \subseteq S$, define $\mathcal{F}(R) = \{F \in \mathcal{F}(S) \mid F \subseteq R\}$. (That is, the multiplicity of F in $\mathcal{F}(R)$ is the same as in $\mathcal{F}(S)$.) We also assume a *conflict relation* $C \subseteq S \times \mathcal{F}(S)$ between objects and regions. We postulate that for all $x \in S$ and $F \in \mathcal{F}(S)$, if $(x, F) \in C$ then F does not rely on x.

As an example consider a set S of $n > d$ points in $\mathbb{R}^d$ in nondegenerate position. Every set $F \subset S$ with d points spans a hyperplane, which in turn defines two open halfspaces $H_1(F)$ and $H_2(F)$. Thus we can define a multiset $\mathcal{F}(S)$, where each set $F \subset S$ of size d gives rise to two regions in $\mathcal{F}(S)$, one for $H_1(F)$ and one for $H_2(F)$. Note that $\mathcal{F}(S)$ is uniform with $b = d$. There is a natural conflict relation: a point $x \in S$ conflicts with a region denoting $H_i(F)$ iff $x \in H_i(F)$. Regions $H_i(F)$ that do not conflict with any points in S are particularly interesting since they arise exactly from those d-sets $F \subset S$ that span a facet of the convex hull of S. This means that constructing the convex hull of S, i.e. determining all its facets, amounts to finding all regions in $\mathcal{F}(S)$ that do not conflict with any point in S. We use conv S to denote the convex hull of S.

For a subset $R \subseteq S$, $\mathcal{F}_0(R)$ will denote the set of $F \in \mathcal{F}(R)$ having no $x \in R$ with $(x, F) \in C$; that is, $\mathcal{F}_0(R)$ is the set of regions over R which do not conflict with any object in R. In our example $\mathcal{F}_0(R)$ contains therefore all d-sets in R that span facets of the convex hull of R.

Clarkson and Shor [CS89] analyzed the incremental computation of $\mathcal{F}_0(S)$. In the general step, $\mathcal{F}_0(R)$ for some subset $R \subseteq S$ is already available, a random element $x \in S \setminus R$ is chosen, and $\mathcal{F}_0(R \cup \{x\})$ is constructed from $\mathcal{F}_0(R)$.

Let $(x_1, \ldots, x_j)$ be a sequence of distinct elements of S, and R_j the set $\{x_1, \ldots, x_j\}$. Let $R_0 = \{\}$, the empty set. The *history* $H = H(x_1, \ldots, x_r)$ for insertion sequence $(x_1, \ldots, x_r)$ is defined as $H = \bigcup_{1 \le i \le r} \mathcal{F}_0(R_i)$. Thus in our example $H(x_1, \ldots, x_r)$ comprises all facets that ever arose while incrementally constructing the convex hull of R_r by successively inserting $x_1, x_2, \ldots, x_r$. Note the somewhat unusual boundary conditions. $H(x_1, \ldots, x_r) = \emptyset$ for $r < d$, $H(x_1, \ldots, x_d)$ consists of two copies of the set $\{x_1, \ldots, x_d\}$, one for each halfspace, and $H(x_1, \ldots, x_{d+1})$ comprises $d+2$ facets, namely the $d+1$ facets of the simplex conv$\{x_1, \ldots, x_{d+1}\}$ and also the second "side" of the facet $\{x_1 \ldots, x_d\}$. Let Π_S be the set of permutations of S. For $\pi = (x_1, \ldots, x_n) \in \Pi_S$, $H_r(\pi)$ or simply H_r denotes the history $H(x_1, \ldots, x_r)$.

First, some simple facts about random permutations, whose proofs we leave to the reader:

Lemma 1 *If $\pi = (x_1, \ldots, x_n)$ is a random permutation of S, then R_j is a*

- We give a simple analysis of the expected behavior of RICs; cf. § 2. We deal with insertions and deletions and derive bounds for the expected number of regions constructed and the expected number of conflicts encountered in the construction. In the case of deletions our bounds are new, but compare [DMT91, Mul91a, Mul91b, Mul91c, Sch91] for related results. In the case of insertions the results were known, but our proofs are simpler and give tight bounds (and not just upper bounds) in many cases.

- We apply the general results on RIC to the problem of maintaining convex hulls in d-dimensional space; cf. § 3. We show that random insertions and deletions take expected time $O(\log n)$ for $d \leq 3$ and time $O(n^{\lfloor d/2 \rfloor - 1})$ otherwise. If the points are in convex position, which is, e.g., the case when Voronoi diagrams are transformed into convex hulls of one higher dimension, the deletion time becomes $\log \log n$ for $d \leq 3$. Schwarzkopf [Sch91] has obtained the same bounds for all $d \geq 6$, Mulmuley [Mul91c] has obtained the same bound for all d but with a more complex construction, and Devillers et al [DMT91] have previously obtained the result for 2-dimensional Voronoi-diagrams.

- We derive a tail estimate for the number of regions constructed in RICs; cf. § 4.

- We study the complexity of a game related to the $O(n \log^* n)$ expected time RICs of [Sei91] and [Dev] and show that the complexity of the game is $\Theta(n \log^* n)$; cf. § 5. This indicates that these expected time bounds do not admit improvements unless significant new algorithmic ideas are introduced.

2 Randomized Incremental Constructions: General Theorems

In this section we give a new analysis of the expected behavior of randomized incremental construction. The novel features of our analysis are:

- the proofs are simple and self-contained; in particular, they do require any $k-$set bounds (as all previous proofs did),

- the bounds are tight in many cases,

- the proof of the bound of the search time (Theorem 4) uses a novel generalization of "backwards analysis",

- the analysis deals with insertions and deletions.

Four Results on Randomized Incremental Constructions*

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November 5, 1991
revised February 26, 1992
revised February 15, 1993

Abstract

We prove four results on randomized incremental constructions (RICs):

- an analysis of the expected behavior under insertion and deletions,
- a fully dynamic data structure for convex hull maintenance in arbitrary dimensions,
- a tail estimate for the space complexity of RICs,
- a lower bound on the complexity of a game related to RICs.

1 Introduction

Randomized incremental construction (RIC) is a powerful paradigm for geometric algorithms [CS89, Mul88, BDS$^+$]. It leads to simple and efficient algorithms for a wide range of geometric problems: line segment intersection [CS89, Mul88], convex hulls [CS89, Sei90], Voronoi diagrams [CS89, MMO91, GKS90, Dev], triangulation of simple polygons [Sei91], and many others. In this paper we make four contributions to the study of RICs.

*A preliminary version of this paper was presented at the 9th Symposium on Theoretical Aspects of Computer Science (STACS 92)

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