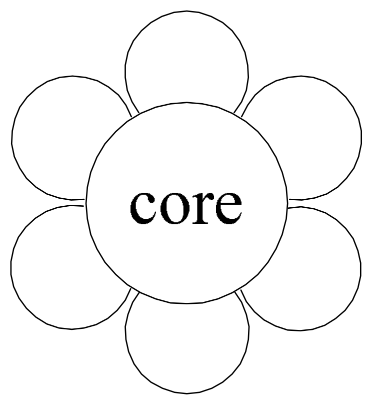
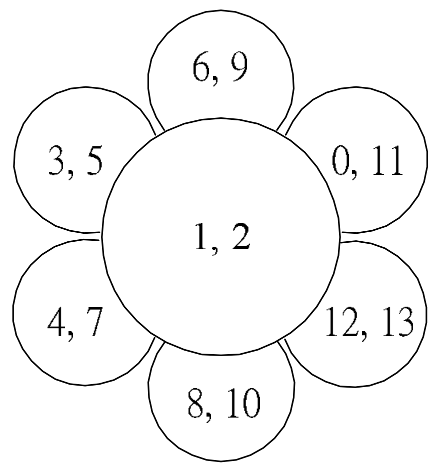
Sunflowers

- Fix $p \in \mathbb{Z}^+$ and $\ell \in \mathbb{Z}^+$.
- A **sunflower** is a family of p sets $\{ P_1, P_2, \ldots, P_p \}$, called **petals**, each of cardinality at most ℓ.
- Furthermore, all pairs of sets in the family must have the same intersection (called the **core** of the sunflower).



A Sample Sunflower

$$\{\{1,2,3,5\},\{1,2,6,9\},\{0,1,2,11\},$$
$$\{1,2,12,13\},\{1,2,8,10\},\{1,2,4,7\}\}.$$



The Erdős-Rado Lemma

Lemma 88 *Let $\mathcal{Z}$ be a family of more than $M \stackrel{\Delta}{=} (p-1)^\ell \ell!$ nonempty sets, each of cardinality ℓ or less. Then $\mathcal{Z}$ must contain a sunflower (with p petals).*

- Induction on ℓ.
- For $\ell = 1$, p different singletons form a sunflower (with an empty core).
- Suppose $\ell > 1$.
- Consider a *maximal* subset $\mathcal{D} \subseteq \mathcal{Z}$ of *disjoint* sets.
  - Every set in $\mathcal{Z} - \mathcal{D}$ intersects some set in $\mathcal{D}$.

The Proof of the Erdős-Rado Lemma (continued)

For example,

$$\begin{aligned}
\mathcal{Z} &= \{\{1,2,3,5\},\{1,3,6,9\},\{0,4,8,11\},\\
&\quad \{4,5,6,7\},\{5,8,9,10\},\{6,7,9,11\}\},\\
\mathcal{D} &= \{\{1,2,3,5\},\{0,4,8,11\}\}.
\end{aligned}$$

The Proof of the Erdős-Rado Lemma (continued)

- Suppose $\mathcal{D}$ contains at least p sets.
  - $\mathcal{D}$ constitutes a sunflower with an empty core.
- Suppose $\mathcal{D}$ contains fewer than p sets.
  - Let C be the union of all sets in $\mathcal{D}$.
  - $|\,C\,| \leq (p-1)\ell$.
  - C intersects every set in $\mathcal{Z}$ by $\mathcal{D}$'s maximality.
  - There is a $d \in C$ that intersects more than $\frac{M}{(p-1)\ell} = (p-1)^{\ell-1}(\ell-1)!$ sets in $\mathcal{Z}$.
  - Consider $\mathcal{Z}' = \{\, Z - \{\, d\,\} : Z \in \mathcal{Z}, d \in Z\,\}$.

The Proof of the Erdős-Rado Lemma (concluded)

- (continued)
  - $\mathcal{Z}'$ has more than $M' \stackrel{\Delta}{=} (p-1)^{\ell-1}(\ell-1)!$ sets.
  - M' is just M with ℓ replaced with $\ell - 1$.
  - $\mathcal{Z}'$ contains a sunflower by induction, say

$$\{ P_1, P_2, \ldots, P_p \}.$$

  - Now,

$$\{ P_1 \cup \{ d \}, P_2 \cup \{ d \}, \ldots, P_p \cup \{ d \} \}$$

    is a sunflower in $\mathcal{Z}$.

Comments on the Erdős-Rado Lemma

- A family of more than M sets must contain a sunflower.
- **Plucking** a sunflower means replacing the sets in the sunflower by its core.
- By *repeatedly* finding a sunflower and plucking it, we can reduce a family with more than M sets to a family with at most M sets.
- If $\mathcal{Z}$ is a family of sets, the above result is denoted by pluck($\mathcal{Z}$).
- pluck($\mathcal{Z}$) is not unique.[a]

[a] It depends on the sequence of sunflowers one plucks. Fortunately, this issue is not material to the proof.

An Example of Plucking

- Recall the sunflower on p. 811:

$$\begin{aligned}\mathcal{Z} &= \{\{1,2,3,5\},\{1,2,6,9\},\{0,1,2,11\},\\ &\quad \{1,2,12,13\},\{1,2,8,10\},\{1,2,4,7\}\}\end{aligned}$$

- Then

$$\text{pluck}(\mathcal{Z}) = \{\{1,2\}\}.$$

Razborov's Theorem

Theorem 89 (Razborov, 1985) *There is a constant c such that for large enough n, all monotone circuits for* $\text{CLIQUE}_{n,k}$ *with $k = n^{1/4}$ have size at least $n^{cn^{1/8}}$.*

- We shall approximate any monotone circuit for $\text{CLIQUE}_{n,k}$ by a restricted kind of crude circuit.
- The approximation will proceed in steps: one step for each gate of the monotone circuit.
- Each step introduces few errors (false positives and false negatives).
- Yet, the final crude circuit has exponentially many errors.

The Proof

- Fix $k = n^{1/4}$.
- Fix $\ell = n^{1/8}$.
- Note that[a]

$$2\binom{\ell}{2} \leq k-1.$$

- p will be fixed later to be $n^{1/8} \log n$.
- Fix $M = (p-1)^{\ell} \ell!$.
  - Recall the Erdős-Rado lemma (p. 812).

[a]Corrected by Mr. Moustapha Bande (D98922042) on January 5, 2010.

The Proof (continued)

- Each crude circuit used in the approximation process is of the form $\mathrm{CC}(X_1, X_2, \ldots, X_m)$, where:
  - $X_i \subseteq V$.
  - $|X_i| \leq \ell$.
  - $m \leq M$.
- It answers true if any X_i is a clique.
- We shall show how to approximate any monotone circuit for $\textsc{clique}_{n,k}$ by such a crude circuit, inductively.
- The induction basis is straightforward:
  - Input gate g_{ij} is the crude circuit $\mathrm{CC}(\{i, j\})$.

The Proof (continued)

- A monotone circuit is the OR or AND of two subcircuits.
- We will build approximators of the overall circuit from the approximators of the two subcircuits.
  - Start with two crude circuits CC($\mathcal{X}$) and CC($\mathcal{Y}$).
  - $\mathcal{X}$ and $\mathcal{Y}$ are two families of at most M sets of nodes, each set containing at most ℓ nodes.
  - We will construct the approximate OR and the approximate AND of these subcircuits.
  - Then show both approximations introduce few errors.

The Proof: OR

- $\mathrm{CC}(\mathcal{X} \cup \mathcal{Y})$ is *equivalent to* the OR of $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$.
  - Trivially, a node set $\mathcal{C} \in \mathcal{X} \cup \mathcal{Y}$ is a clique if and only if $\mathcal{C} \in \mathcal{X}$ is a clique or $\mathcal{C} \in \mathcal{Y}$ is a clique.
- Violations in using $\mathrm{CC}(\mathcal{X} \cup \mathcal{Y})$ occur when $|\,\mathcal{X} \cup \mathcal{Y}\,| > M$.
- Such violations are eliminated by using

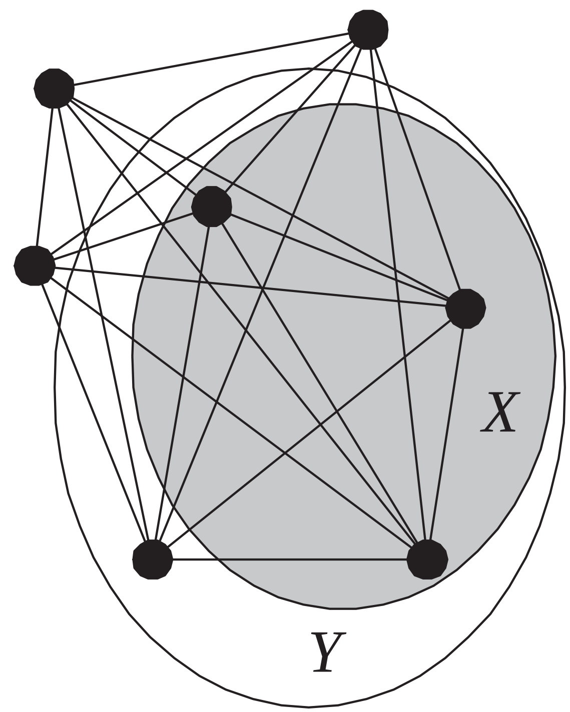
$$\mathrm{CC}(\mathrm{pluck}(\mathcal{X} \cup \mathcal{Y}))$$

as the approximate OR of $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$.

The Proof: OR (continued)

- If $\text{CC}(\mathcal{Z})$ is true, then $\text{CC}(\text{pluck}(\mathcal{Z}))$ must be true.
  - The quick reason: If Y is a clique, then a subset of Y must also be a clique.
  - Let $Y \in \mathcal{Z}$ be a clique.
  - There must exist an $X \in \text{pluck}(\mathcal{Z})$ such that $X \subseteq Y$.
  - This X is also a clique.

The Proof: OR (continued)



The Proof: OR (concluded)

- $\text{CC}(\text{pluck}(\mathcal{X} \cup \mathcal{Y}))$ *introduces* a **false positive** if a negative example makes both $\text{CC}(\mathcal{X})$ and $\text{CC}(\mathcal{Y})$ return false but makes $\text{CC}(\text{pluck}(\mathcal{X} \cup \mathcal{Y}))$ return true.
- $\text{CC}(\text{pluck}(\mathcal{X} \cup \mathcal{Y}))$ *introduces* a **false negative** if a positive example makes either $\text{CC}(\mathcal{X})$ or $\text{CC}(\mathcal{Y})$ return true but makes $\text{CC}(\text{pluck}(\mathcal{X} \cup \mathcal{Y}))$ return false.
- We next count the number of false positives and false negatives introduced[a] by $\text{CC}(\text{pluck}(\mathcal{X} \cup \mathcal{Y}))$.
- Let us work on false negatives for OR first.

[a] Compared with $\text{CC}(\mathcal{X} \cup \mathcal{Y})$ of course.

The Number of False Negatives[a]

Lemma 90 CC(pluck($\mathcal{X} \cup \mathcal{Y}$)) *introduces no false negatives.*

- Each plucking replaces sets in a crude circuit by their common subset.
- This makes the test for cliqueness less stringent.[b]

---

[a]CC(pluck($\mathcal{X} \cup \mathcal{Y}$)) introduces a false negative if a positive example makes either CC($\mathcal{X}$) or CC($\mathcal{Y}$) return true but makes CC(pluck($\mathcal{X} \cup \mathcal{Y}$)) return false.

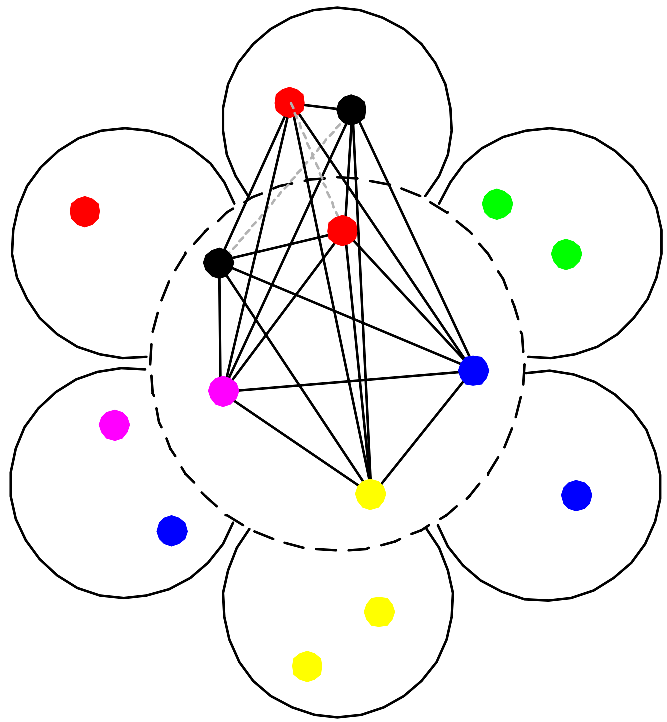
[b]Recall p. 823.

The Number of False Positives

Lemma 91 CC(pluck($\mathcal{X} \cup \mathcal{Y}$)) *introduces at most* $\frac{2M}{p-1}\, 2^{-p}(k-1)^n$ *false positives.*

- Each plucking operation replaces the sunflower $\{ Z_1, Z_2, \ldots, Z_p \}$ with its common core Z.
- A false positive is *necessarily* a coloring such that:
  - There is a pair of identically colored nodes in *each* petal Z_i (and so CC$(Z_1, Z_2, \ldots, Z_p)$ returns false).
  - But the core contains distinctly colored nodes (thus forming a clique).
  - This implies at least one node from each identical-color pair was plucked away.

Proof of Lemma 91 (continued)



Proof of Lemma 91 (continued)

- We now count the number of such colorings.
- Color nodes in V at random with $k-1$ colors.
- Let $R(X)$ denote the event that there are repeated colors in set X.

Proof of Lemma 91 (continued)

- Now

$$
\begin{aligned}
& \text{prob}[\, R(Z_1) \wedge \cdots \wedge R(Z_p) \wedge \neg R(Z)\,] & (24) \\
\leq\; & \text{prob}[\, R(Z_1) \wedge \cdots \wedge R(Z_p) \,|\, \neg R(Z)\,] \\
=\; & \prod_{i=1}^{p} \text{prob}[\, R(Z_i) \,|\, \neg R(Z)\,] \\
\leq\; & \prod_{i=1}^{p} \text{prob}[\, R(Z_i)\,]. & (25)
\end{aligned}
$$

  – First equality holds because $R(Z_i)$ are independent given $\neg R(Z)$ as Z contains their *only common* nodes.
  – Last inequality holds as the likelihood of repetitions in Z_i decreases given no repetitions in its subset Z.

Proof of Lemma 91 (continued)

- Consider two nodes in Z_i.
- The probability that they have identical color is

$$\frac{1}{k-1}.$$

- Now

$$\text{prob}[\, R(Z_i)\,] \leq \frac{\binom{|Z_i|}{2}}{k-1} \leq \frac{\binom{\ell}{2}}{k-1} \leq \frac{1}{2}.$$

- So the probability[a] that a random coloring is a *new* false positive is at most 2^{-p} by inequality (25) on p. 830.

[a]Proportion, if you so prefer.

Proof of Lemma 91 (continued)

- As there are $(k-1)^n$ different colorings, *each* plucking introduces at most $2^{-p}(k-1)^n$ false positives.
- Recall that $|\,\mathcal{X} \cup \mathcal{Y}\,| \leq 2M$.
- When the procedure pluck($\mathcal{X} \cup \mathcal{Y}$) ends, the set system contains $\leq M$ sets.

Proof of Lemma 91 (concluded)

- Each plucking reduces the number of sets by $p-1$.
- Hence at most $2M/(p-1)$ pluckings occur in pluck$(\mathcal{X} \cup \mathcal{Y})$.
- At most

$$\frac{2M}{p-1}\, 2^{-p}(k-1)^n$$

false positives are introduced.[a]

[a] Note that the numbers of errors are added not multiplied. Recall that we count how many *new* errors are introduced by each approximation step. Contributed by Mr. Ren-Shuo Liu (`D98922016`) on January 5, 2010.

The Proof: AND

- The approximate AND of crude circuits $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$ is

$$\mathrm{CC}(\mathrm{pluck}(\{\, X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y}, |\, X_i \cup Y_j \,| \leq \ell \,\})).$$

- We need to count the number of errors this approximate AND introduces on the positive and negative examples.

The Proof: AND (continued)

- The approximate AND *introduces* a **false positive** if a negative example makes either $\mathrm{CC}(\mathcal{X})$ or $\mathrm{CC}(\mathcal{Y})$ return false but makes the approximate AND return true.
- The approximate AND *introduces* a **false negative** if a positive example makes both $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$ return true but makes the approximate AND return false.
- Introduction of errors means we ignore scenarios where the AND of $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$ is already wrong.

The Proof: AND (continued)

- $\mathrm{CC}(\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \})$ introduces no false positives and no false negatives over our positive and negative examples.[a]
  - Suppose $\mathrm{CC}(\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \})$ returns true.
  - Then some $X_i \cup Y_j$ is a clique.
  - Thus $X_i \in \mathcal{X}$ and $Y_j \in \mathcal{Y}$ are cliques, making both $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$ return true.
  - So $\mathrm{CC}(\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \})$ introduces no false positives.

[a] Unlike the OR case on p. 822, we are not claiming that $\mathrm{CC}(\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \})$ is *equivalent to* the AND of $\mathrm{CC}(\mathcal{X})$ and $\mathrm{CC}(\mathcal{Y})$. Equivalence is more than we need in either case.

The Proof: AND (concluded)

- (continued)
  - On the other hand, suppose *both* $CC(\mathcal{X})$ and $CC(\mathcal{Y})$ accept a positive example with a clique $\mathcal{C}$ of size k.
  - This clique $\mathcal{C}$ must contain an $X_i \in \mathcal{X}$ and a $Y_j \in \mathcal{Y}$.
  - As this clique $\mathcal{C}$ also contains $X_i \cup Y_j$,[a] the new circuit returns true.
  - $CC(\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \})$ introduces no false negatives.
- We now bound the number of false positives and false negatives introduced[b] by the approximate AND.

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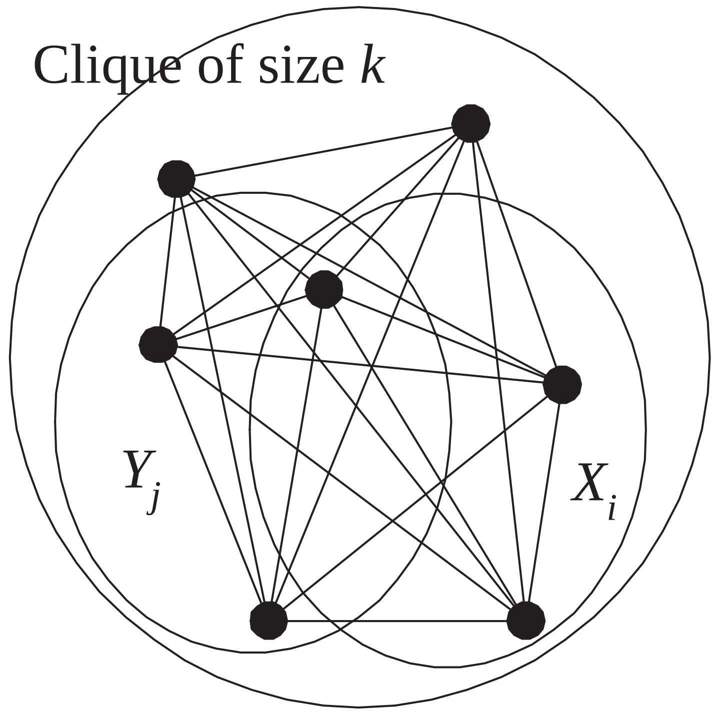
[a]See next page.

[b]Compared with $CC(\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \})$ of course.


Clique of size k
Y_j
X_i

The Number of False Positives

Lemma 92 *The approximate* AND *introduces at most* $M^2 2^{-p}(k-1)^n$ *false positives.*

- We prove this claim in stages.
- We already knew $\mathrm{CC}(\{\, X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \,\})$ introduces no false positives.[a]
- $\mathrm{CC}(\{\, X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y}, \mid X_i \cup Y_j \mid \leq \ell \,\})$ introduces no *additional* false positives because we are testing potentially fewer sets for cliqueness.

---
[a] Recall p. 836.

Proof of Lemma 92 (concluded)

- $|\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y}, |X_i \cup Y_j| \leq \ell \}| \leq M^2$.
- Each plucking reduces the number of sets by $p - 1$.
- So pluck($\{ X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y}, |X_i \cup Y_j| \leq \ell \}$) involves $\leq M^2/(p-1)$ pluckings.
- Each plucking introduces at most $2^{-p}(k-1)^n$ false positives by the proof of Lemma 91 (p. 827).
- The desired upper bound is

$$[\, M^2/(p-1) \,]\, 2^{-p}(k-1)^n \leq M^2 2^{-p}(k-1)^n.$$

The Number of False Negatives

Lemma 93 *The approximate* AND *introduces at most* $M^2\binom{n-\ell-1}{k-\ell-1}$ *false negatives.*

- We again prove this claim in stages.
- We knew $\text{CC}(\{\, X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y} \,\})$ introduces no false negatives.[a]

---

[a]Recall p. 836.

Proof of Lemma 93 (continued)

- $\mathrm{CC}(\{\, X_i \cup Y_j : X_i \in \mathcal{X}, Y_j \in \mathcal{Y}, |\, X_i \cup Y_j \,| \leq \ell \,\})$ introduces $\leq M^2 \binom{n-\ell-1}{k-\ell-1}$ false negatives.
  - Deletion of set $Z \stackrel{\Delta}{=} X_i \cup Y_j$ larger than ℓ introduces false negatives *only if* Z is part of a clique.
  - There are $\binom{n-|\,Z\,|}{k-|\,Z\,|}$ such cliques.
    * It is the number of positive examples whose clique contains Z.
  - $\binom{n-|\,Z\,|}{k-|\,Z\,|} \leq \binom{n-\ell-1}{k-\ell-1}$ as $|\,Z\,| > \ell$.
  - There are at most M^2 such Zs.

Proof of Lemma 93 (concluded)

- Plucking introduces no false negatives.
  - Recall that if $\text{CC}(\mathcal{Z})$ is true, then $\text{CC}(\text{pluck}(\mathcal{Z}))$ must be true.[a]

---

[a]Recall p. 823.

Two Summarizing Lemmas

From Lemmas 91 (p. 827) and 92 (p. 839), we have:

Lemma 94 *Each approximation step introduces at most* $M^2 2^{-p}(k-1)^n$ *false positives.*

From Lemmas 90 (p. 826) and 93 (p. 841), we have:

Lemma 95 *Each approximation step introduces at most* $M^2\binom{n-\ell-1}{k-\ell-1}$ *false negatives.*

The Proof (continued)

- The above two lemmas show that each approximation step introduces "few" false positives and false negatives.
- We next show that the resulting crude circuit has "a lot" of false positives or false negatives.

The Final Crude Circuit

Lemma 96 *Every final crude circuit is:*

1. *Identically false—thus wrong on all positive examples.*
2. *Or outputs true on at least half of the negative examples.*

- Suppose it is not identically false.
- By construction, it accepts at least those graphs that have a clique on some set X of nodes, with

$$|\,X\,| \leq \ell = n^{1/8} < n^{1/4} = k.$$

Proof of Lemma 96 (concluded)

- The proof of Lemma 91 (p. 827ff) shows that at least half of the colorings assign different colors to nodes in X.
- So at least half of the colorings — thus negative examples — have a clique in X and are accepted.

The Proof (continued)

- Recall the constants on p. 819:

$$
\begin{aligned}
k &\stackrel{\Delta}{=} n^{1/4}, \\
\ell &\stackrel{\Delta}{=} n^{1/8}, \\
p &\stackrel{\Delta}{=} n^{1/8} \log n, \\
M &\stackrel{\Delta}{=} (p-1)^{\ell} \ell! < n^{(1/3) n^{1/8}} \quad \text{for large } n.
\end{aligned}
$$

The Proof (continued)

- Suppose the final crude circuit is identically false.
  - By Lemma 95 (p. 844), each approximation step introduces at most $M^2\binom{n-\ell-1}{k-\ell-1}$ false negatives.
  - There are $\binom{n}{k}$ positive examples.
  - The original monotone circuit for $\text{CLIQUE}_{n,k}$ has at least

$$\frac{\binom{n}{k}}{M^2\binom{n-\ell-1}{k-\ell-1}} \geq \frac{1}{M^2}\left(\frac{n-\ell}{k}\right)^{\ell} \geq n^{(1/12)n^{1/8}}$$

gates for large n.

The Proof (concluded)

- Suppose the final crude circuit is not identically false.
  - Lemma 96 (p. 846) says that there are at least $(k-1)^n/2$ false positives.
  - By Lemma 94 (p. 844), each approximation step introduces at most $M^2 2^{-p}(k-1)^n$ false positives
  - The original monotone circuit for $\text{CLIQUE}_{n,k}$ has at least

$$\frac{(k-1)^n/2}{M^2 2^{-p}(k-1)^n} = \frac{2^{p-1}}{M^2} \geq n^{(1/3)n^{1/8}}$$

    gates.

Alexander Razborov (1963–)

P $\neq$ NP Proved?

- Razborov's theorem says that there is a monotone language in NP that has no polynomial monotone circuits.
- If we can prove that all monotone languages in P have polynomial monotone circuits, then P $\neq$ NP.
- But Razborov proved in 1985 that some monotone languages in P have no polynomial monotone circuits!