LECTURE 6

Last time

- Limitations of sublinear-time algorithms
- Yao's Minimax Principle
  - Example: testing monotonicity
- Communication complexity

Today

- Communication complexity
- Other models of computation

HW1 resubmission, project guidelines
Sign up for project meetings, scribing, grading

Communication Complexity

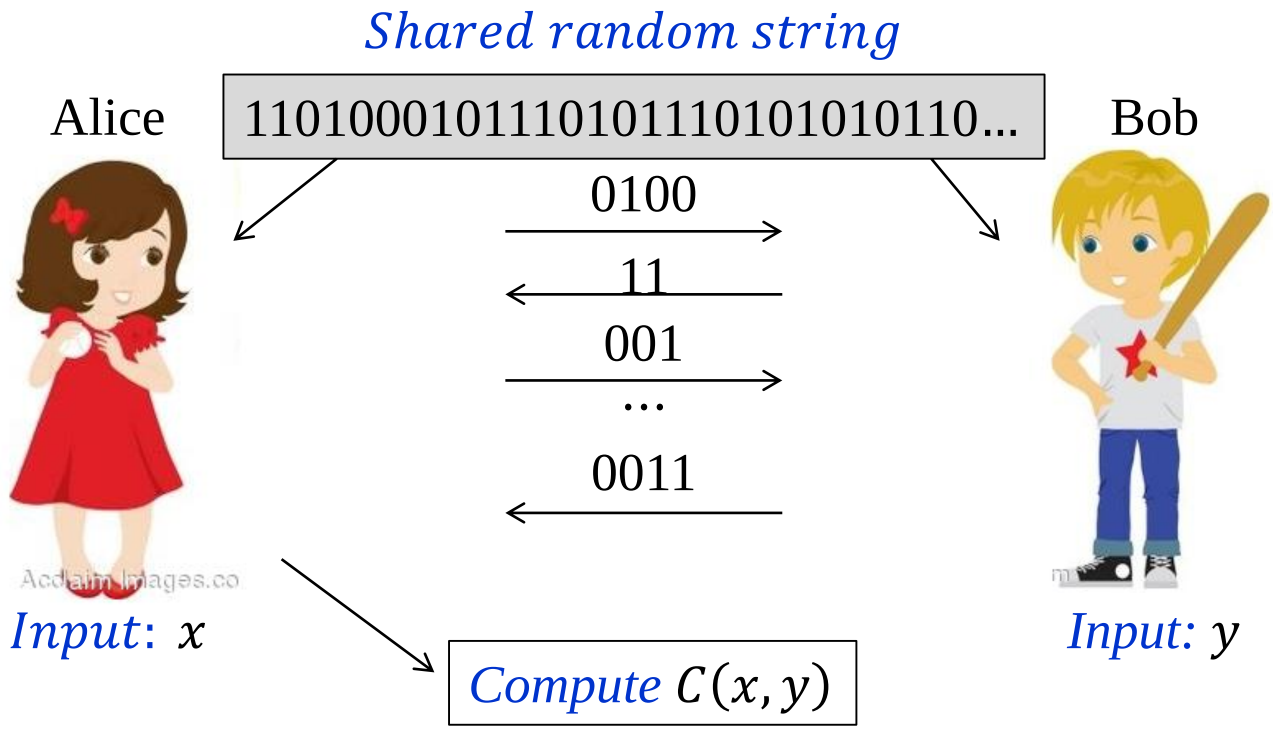
A Method for Proving Lower Bounds

[Blais Brody Matulef 11]

Use known lower bounds
for other models of computation

Partially based on slides by Eric Blais

(Randomized) Communication Complexity



Goal: minimize the number of bits exchanged.

- Communication complexity of a protocol is the maximum number of bits exchanged by the protocol.
- Communication complexity of a function C, denoted $R(C)$, is the communication complexity of the best protocol for computing C.

Example: Set Disjointness $DISJ_k$

Alice   11010001011101011101010110...   Bob

Input: $S \subseteq [n],\ |S| = k$.

Input: $T \subseteq [n],\ |T| = k$

Compute $DISJ_k(S,T)$

$$= \begin{cases} \textbf{accept} & \text{if } S \cap T = \emptyset \\ \textbf{reject} & \text{otherwise} \end{cases}$$

Theorem [Kalyanasundaram Schmitger 92, Razborov 92]

$$R(\mathrm{DISJ}_k) \geq \Omega(k) \text{ for all } k \leq \frac{n}{2}.$$

A lower bound using CC method

Testing if a Boolean function is a k-parity

Linear Functions Over Finite Field $\mathbb{F}_2$

A Boolean function $f: \{0,1\}^n \to \{0,1\}$ is *linear* (also called *parity*) if
$f(x_1, \dots, x_n) = a_1 x_1 + \cdots + a_n x_n$ for some $a_1, \dots, a_n \in \{0,1\}$

no free term

- Work in finite field $\mathbb{F}_2$
  - Other accepted notation for $\mathbb{F}_2$: GF_2 and $\mathbb{Z}_2$
  - Addition and multiplication is mod 2
  - $\boldsymbol{x}=(x_1, \dots, x_n)$, $\boldsymbol{y}=(y_1, \dots, y_n)$, that is, $\boldsymbol{x}, \boldsymbol{y} \in \{0,1\}^n$
    $\boldsymbol{x} + \boldsymbol{y}=(x_1 + y_1, \dots, x_n + y_n)$

example

$$\begin{array}{r} 001001 \\ +\ 011001 \\ \hline 010000 \end{array}$$

Linear Functions Over Finite Field $\mathbb{F}_2$

A Boolean function $f: \{0,1\}^n \rightarrow \{0,1\}$ is *linear* (also called *parity*) if

$$f(x_1, \dots, x_n) = a_1 x_1 + \cdots + a_n x_n \text{ for some } a_1, \dots, a_n \in \{0,1\}$$

$$\Updownarrow$$

$$f(x_1, \dots, x_n) = \sum_{i \in S} x_i \textit{ for some } S \subseteq [n].$$

$[n]$ is a shorthand for $\{1, \dots n\}$

Notation: $\chi_S(x) = \sum_{i \in S} x_i$.

k-Parity Functions

k-Parity Functions

A function $f : \{0,1\}^n \to \{0,1\}$ is a k-parity if

$$f(x) = \chi_S(x) = \sum_{i \in S} x_i$$

for some set $S \subseteq [n]$ of size $|S| = k$.

Testing if a Boolean Function is a k-Parity

Input: Boolean function $f: \{0,1\}^n \to \{0,1\}$ and an integer k

Question: Is the function a k-parity or ε-far from a k-parity ($\geq \varepsilon 2^n$ values need to be changed to make it a k-parity)?

Time:

$O(k \log k)$ [Buhrman, Carcia–Soriano, Matsliah, de Wolf 13]

$\Omega(\min(k, n-k))$ [Blais Brody Matulef 12]

- Today: $\Omega(k)$ for $k \leq n/2$

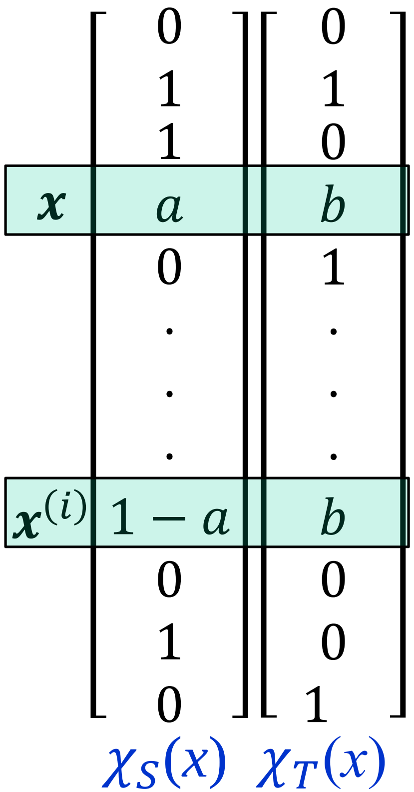
Today's bound implies $\Omega(\min(k, n-k))$

Important Fact About Linear Functions

Fact. Two different linear functions disagree on half of the values.

- Consider functions χ_S and χ_T where $S \neq T$.
  - Let i be an element on which S and T differ (w.l.o.g. $i \in S \setminus T$)
  - Pair up all n-bit strings: $(\boldsymbol{x}, \boldsymbol{x}^{(i)})$ where $\boldsymbol{x}^{(i)}$ is $\boldsymbol{x}$ with the i^{th} bit flipped.
  - For each such pair, $\chi_S(\boldsymbol{x}) \neq \chi_S(\boldsymbol{x}^{(i)})$
    but $\chi_T(\boldsymbol{x}) = \chi_T(\boldsymbol{x}^{(i)})$

    So, χ_S and χ_T differ on exactly one of $\boldsymbol{x}, \boldsymbol{x}^{(i)}$.
  - Since all $\boldsymbol{x}$'s are paired up,
    χ_S and χ_T differ on half of the values.



Corollary. A k'-parity function, where $k' \neq k$, is ½-far from any k-parity.

Reduction from $DISJ_{k/2}$ to Testing k-Parity

- Let T be the best tester for the k-parity property for $\varepsilon = 1/2$
  - query complexity of T is q (testing k–parity).
- We will construct a communication protocol for $DISJ_{k/2}$ that runs T and has communication complexity $2 \cdot q$(testing k–parity).

holds for CC of every protocol for $DISJ_k$

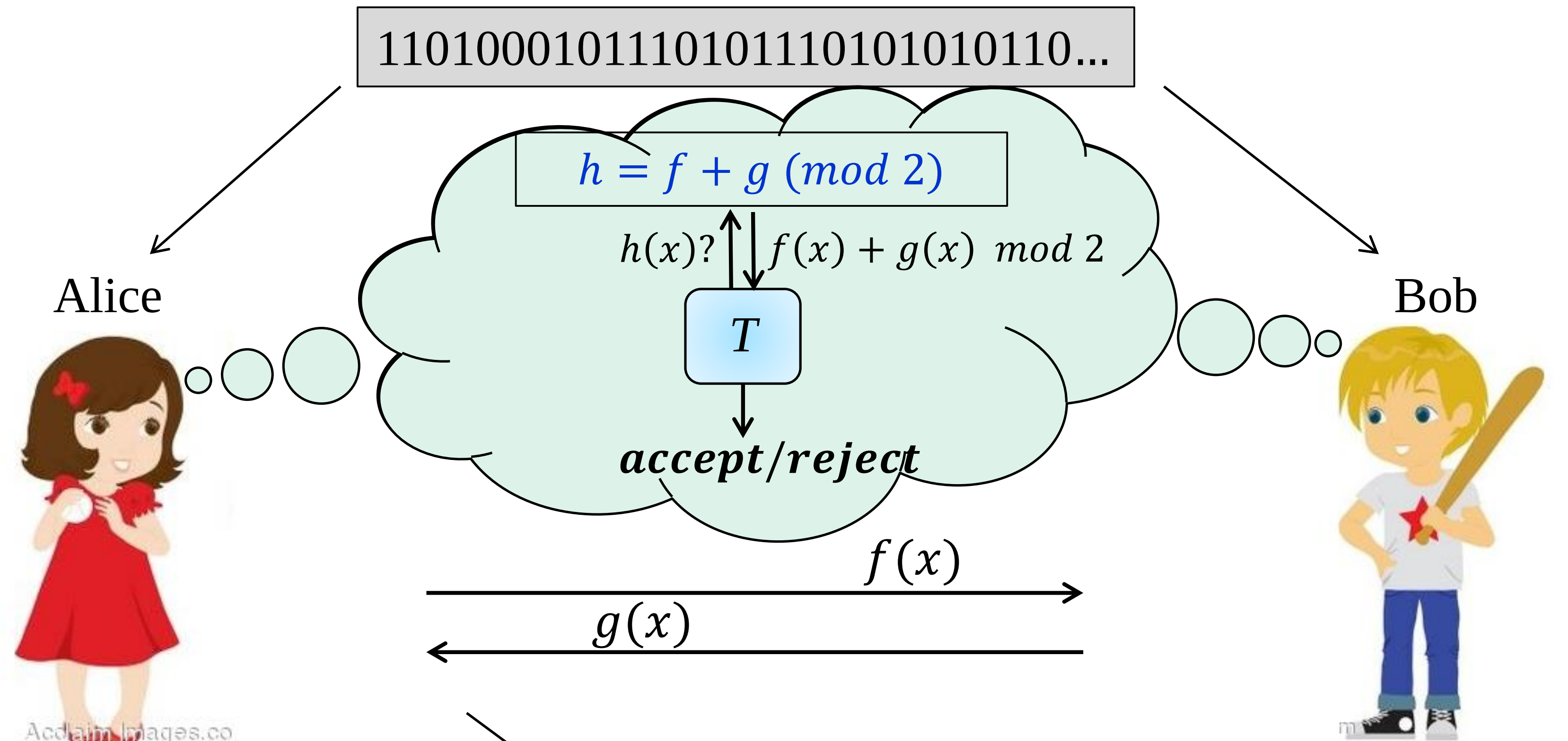
[Hastad Wigderson 07]

- Then $2 \cdot q$(testing k–parity) $\geq R\left(\mathrm{DISJ}_{k/2}\right) \geq \Omega(k/2)$ for $k \leq n/2$

$$\Downarrow$$

q(testing k-parity) $\geq \Omega(k)$ for $k \leq n/2$

Reduction from $DISJ_{k/2}$ to Testing k-Parity



Input: $S \subseteq [n]$, $|S| = k/2$.
Compute: $f = \chi_S$

Output T's answer

Input: $T \subseteq [n]$, $|T| = k/2$
Compute: $g = \chi_T$

- T receives its random bits from the shared random string.

Analysis of the Reduction

Queries: Alice and Bob exchange 2 bits for every bit queried by T

Correctness:

- $h = f + g \ (mod\ 2) = \chi_S + \chi_T \ (mod\ 2) = \chi_{S\Delta T}$
- $|S\Delta T| = |S| + |T| - 2|S \cap T|$

- $|S\Delta T| = \begin{cases} k & \text{if } S\cap T = \emptyset \\ \leq k-2 & \text{if } S\cap T \neq \emptyset \end{cases}$

$$h \text{ is } \begin{cases} k\text{-parity} & \text{if } S\cap T = \emptyset \\ k'\text{-parity where } k' \neq k & \text{if } S\cap T \neq \emptyset \end{cases}$$

1/2-far from every k-parity

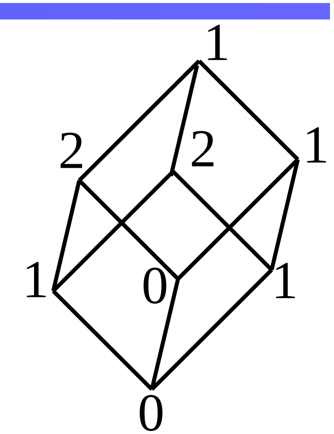
Summary: q(testing k-parity) $\geq \Omega(k)$ for $k \leq n/2$

Testing Lipschitz Property on Hypercube

Lower Bound

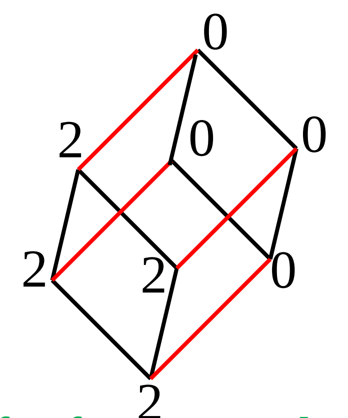
Lipschitz Property of Functions f: $\{0,1\}^n \rightarrow \mathbf{R}$

- A function $f : \{0,1\}^n \rightarrow \mathrm{R}$ is Lipschitz
  if changing a bit of x changes $f(x)$ by at most 1.



Lipschitz

- Is f Lipschitz or ε-far from Lipschitz
  (f has to change on many points to become Lipschitz)?
  - Edge $x - y$ is violated by f if $|f(x) - f(y)| > 1$.



$\frac{1}{2}$-far from Lipschitz

Time:

- $O(n/\varepsilon)$, logarithmic in the size of the input, 2^n
  [Chakrabarty Seshadhri]
- $\Omega(n)$ [Jha Raskhodnikova]

Testing Lipschitz Property

Theorem

Testing Lipschitz property of functions f: $\{0,1\}^n \rightarrow \{0,1,2\}$ requires $\Omega(n)$ queries.

Prove it.

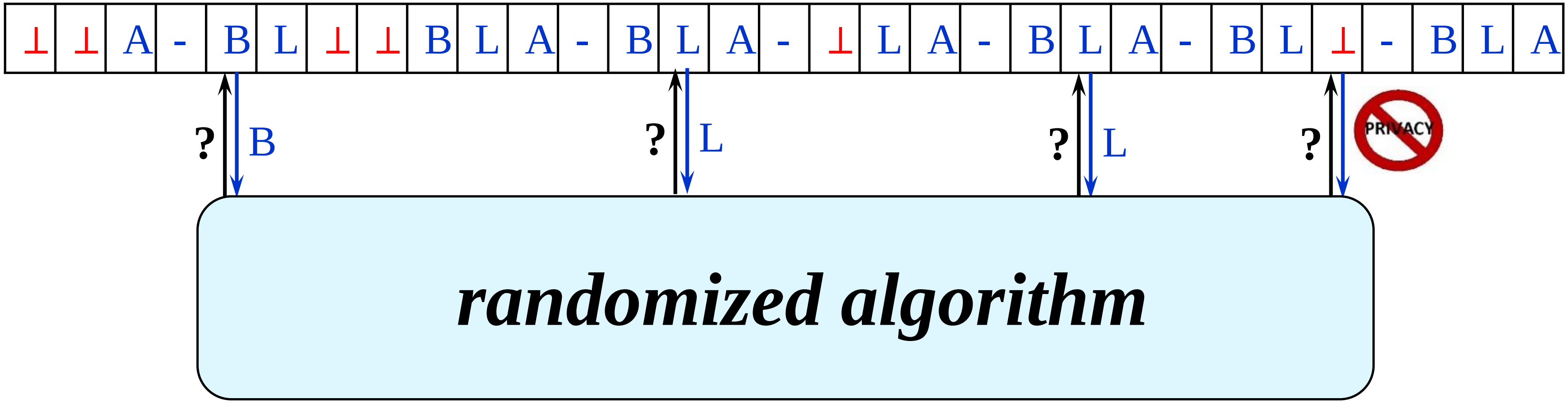
Summary of Lower Bound Methods

- Yao's Principle
  - testing membership in 1*, sortedness of a list and monotonicity of Boolean functions

- Reductions from communication complexity problems
  - testing if a Boolean function is a k-parity

Other Models of Sublinear Computation

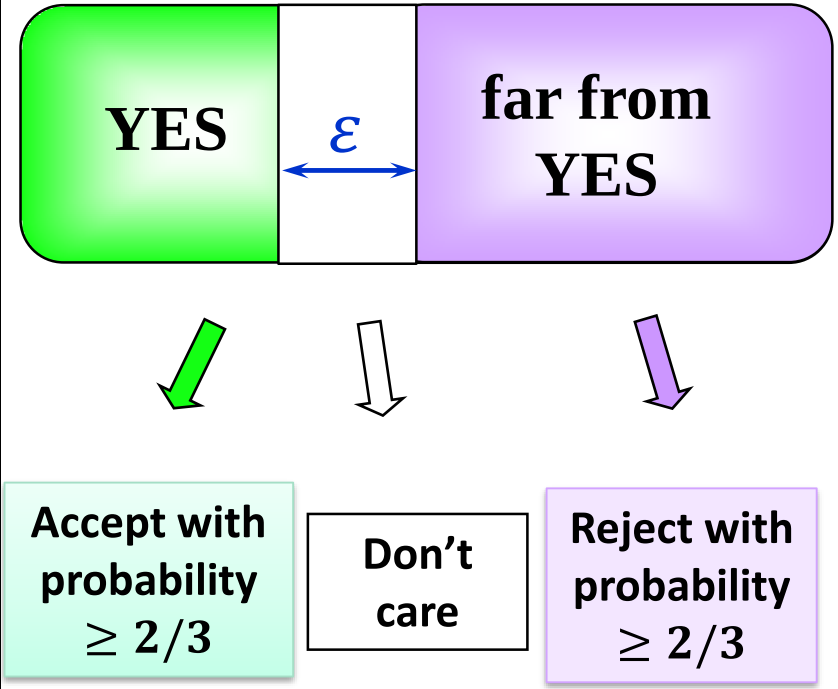
Algorithms Resilient to Erasures (or Errors)



- $\leq \boldsymbol{\alpha}$ fraction of the input is erased (or modified) adversarially before algorithm runs
- Algorithm does not know in advance what's erased (or modified)
- Can we still perform computational tasks?

Property Testing

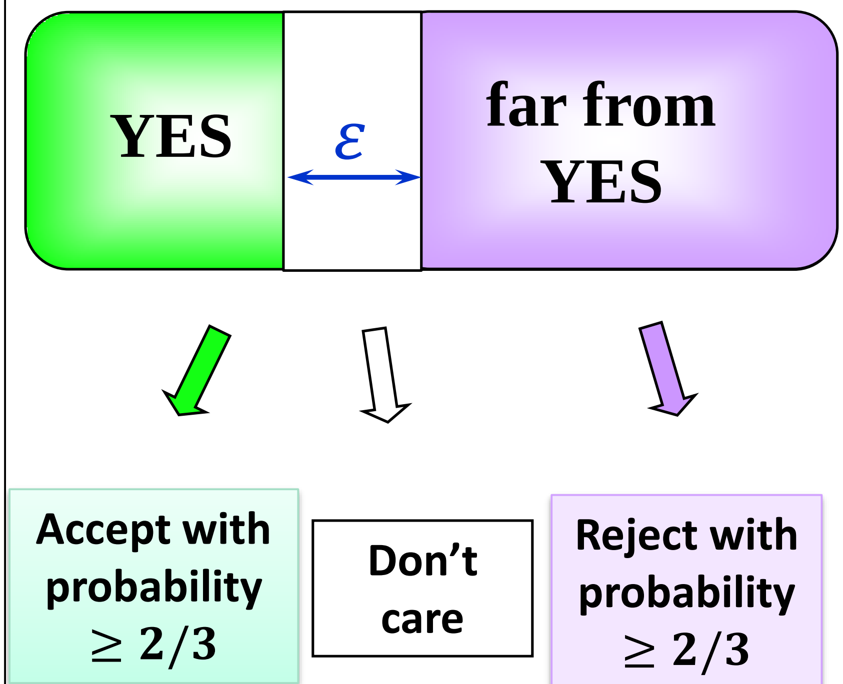
Property Tester [Rubinfeld Sudan 96, Goldreich Goldwasser Ron 98]



Two objects are at distance ε = they differ in an ε fraction of places

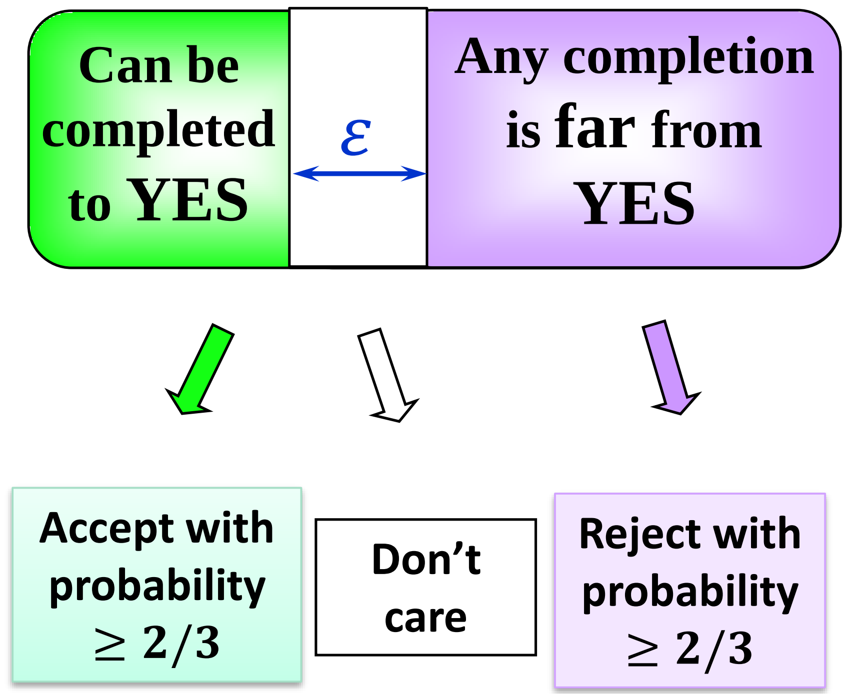
Property Testing with Erasures

Property Tester [Rubinfeld Sudan 96, Goldreich Goldwasser Ron 98]



Erasure-Resilient Property Tester [Dixit Raskhodnikova Thakurta Varma 16]

- $\leq \alpha$ fraction of the input is erased adversarially



Two objects are at distance ε = they differ in an ε fraction of places

Can We Make Testers α-Erasure-Resilient?

It is easy if a tester makes only **uniform** queries
(and the property is **extendable**).

- Use the original tester as black box and ignore erasures:

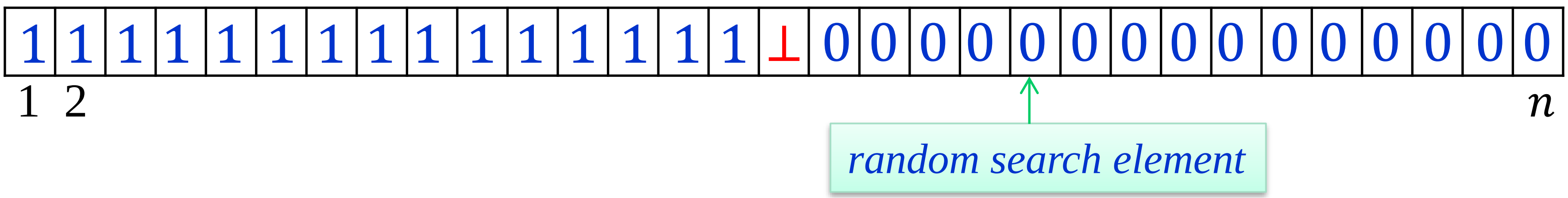
  $O\left(\frac{1}{1-\alpha}\right)$ factor query complexity overhead for all $\alpha \in (0,1)$.

- Applies to many properties
  - Monotonicity over poset domains
    [Fischer Lehman Newman Raskhodnikova Rubinfeld Samorodnitsky 02]
  - Convexity of black and white images
    [Berman Murzabulatov Raskhodnikova 16]
  - Boolean arrays having at most k alternations in values
  - …

Erasure-Resilient Sortedness Tester?

Example: Testing sortedness of n-element arrays

- Every uniform tester requires $\Omega(\sqrt{n})$ queries.
- [EKKRV00] (optimal) tester that makes $O(\log n)$ queries



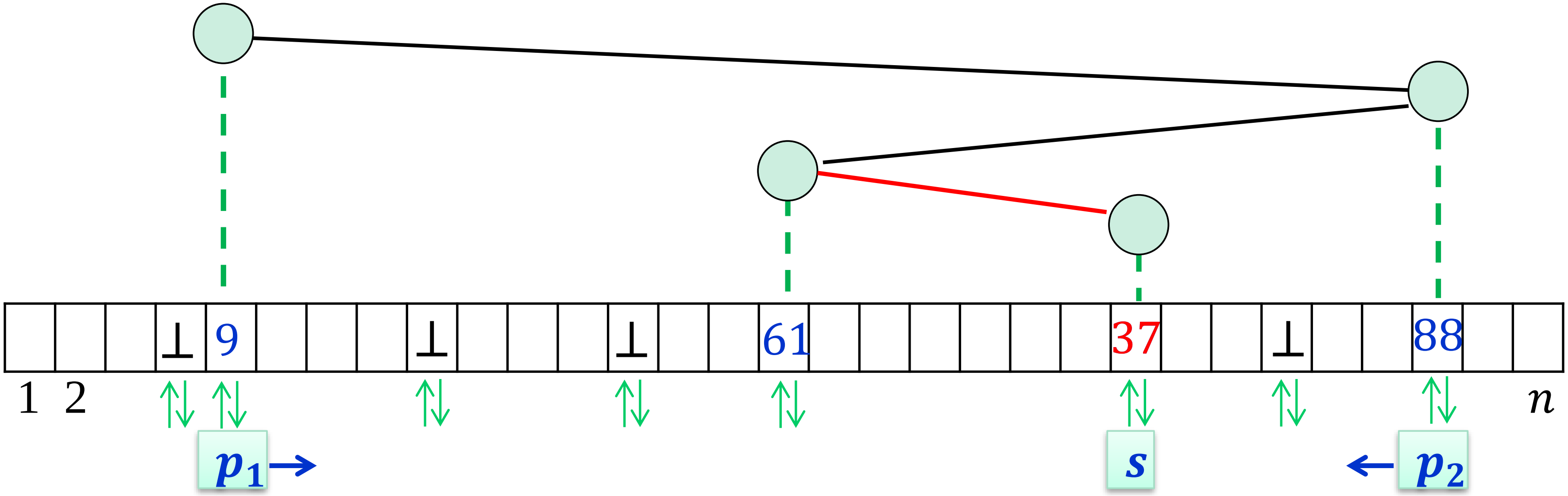
- Can we make it erasure-resilient $O\left(\frac{1}{1-\alpha}\right)$ factor overhead?
- All known optimal sortedness testers [EKKRV00, BGJRW09, CS13a] break with just one erasure.

Known optimal testers for monotonicity, Lipschitz property and convexity of functions [GGLRS00, DGLRRS99, EKKRV00, F04, CS13a, CS13b, CST14, BRY14, BRY14, CDST15, KMS15, BB16, JR13, CS13a, BRY14, BRY14, CDJS15, PRR03, BRY14] **break on a constant number of erasures**.

Erasure-Resilient Sortedness Tester

Input: ε,α ∈ (0,1); query access to an array

1. Repeat **Θ(1/ε)** times:
   a. Sample uniformly until you get a nonerased *search* point s.
   b. Binary search for s with uniform nonerased *split points*.
   c. **Reject** if there are violations along the search path.
2. **Accept** if no violations were found.



Analysis of the Sortedness Tester

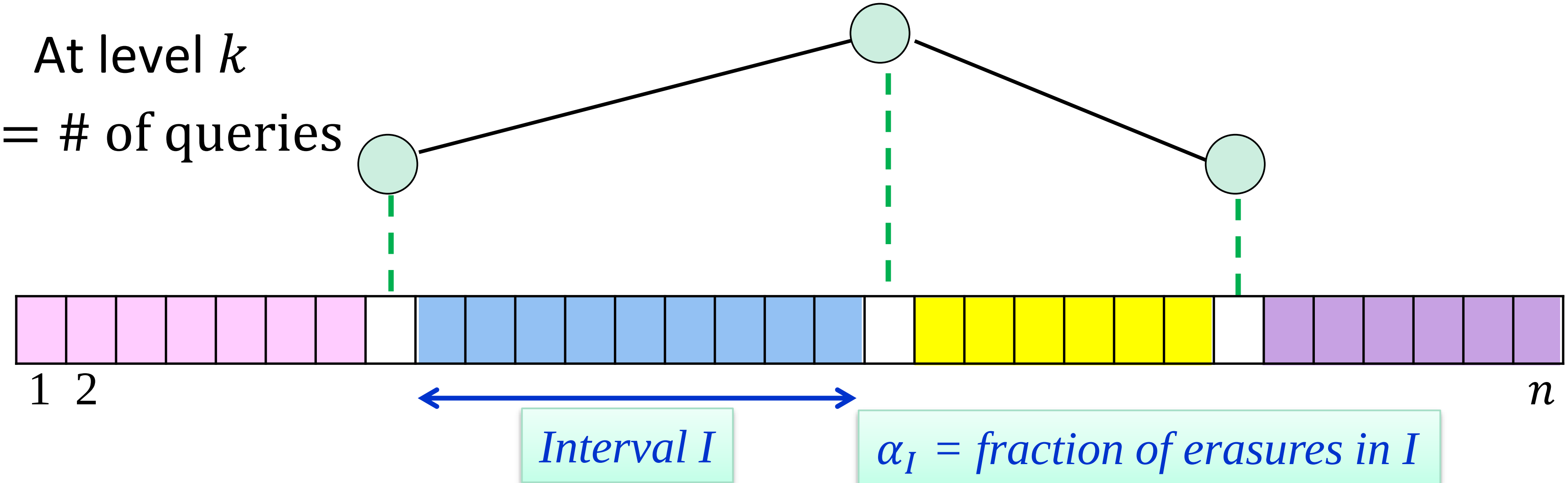
1. Array is sorted $\Longrightarrow$ tester accepts
2. Array is ε-far from sorted $\Longrightarrow$ one iteration rejects with probability ≥ **ε**
   - Need to repeat only Θ(1/ε) times to get error probability 2/3
3. Want to show: expected # of queries per iteration is $O\left(\frac{\log n}{1-\alpha}\right)$
   - Tester traverses a uniformly random search path in a random binary search tree.
   - The # of levels in a random binary search is $O(\log n)$ w.h.p.

Claim. Expected # of queries to one level of binary search is $O\left(\frac{1}{1-\alpha}\right)$

Expected Number of Queries in One Iteration

At level k

$\boldsymbol{Q}$ = # of queries



$$\Pr[\text{search point } \boldsymbol{s} \text{ is in } I] = \frac{\#\text{ nonerased points in I}}{\text{total \# nonerased points}} \leq \frac{|\mathrm{I}|(1-\alpha_I)}{n(1-\alpha)}$$

$$\mathbb{E}\,[\mathrm{Q}] = \sum_{\text{intervals } I \text{ in level } k} E[Q \mid s \in I] \cdot \Pr[s \in I]$$

$$= \sum_{I} \cancel{\frac{1}{1-\alpha_I}} \cdot \frac{|\mathrm{I}|\,\cancel{(1-\alpha_I)}}{n(1-\alpha)} \leq \frac{1}{1-\alpha}$$

What We Proved

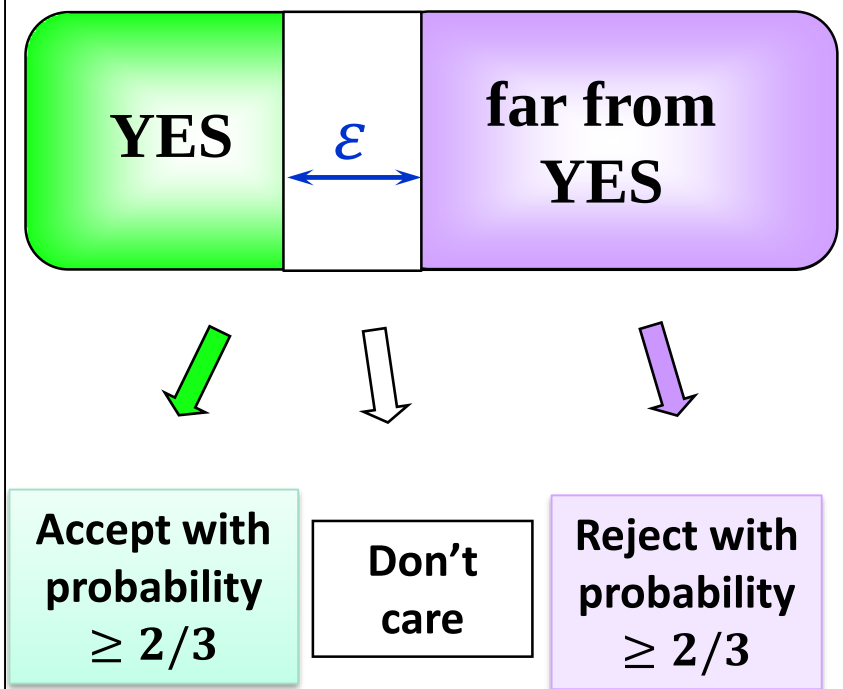
- [Dixit Raskhodnikova Thakurta Varma 16]

Theorem

Our $\boldsymbol{\alpha}$-erasure-resilient $\boldsymbol{\varepsilon}$-tester for sortedness of $\boldsymbol{n}$-element arrays makes $O\left(\frac{\log n}{\varepsilon(1-\alpha)}\right)$ queries for all $\alpha, \varepsilon \in (0,1)$.

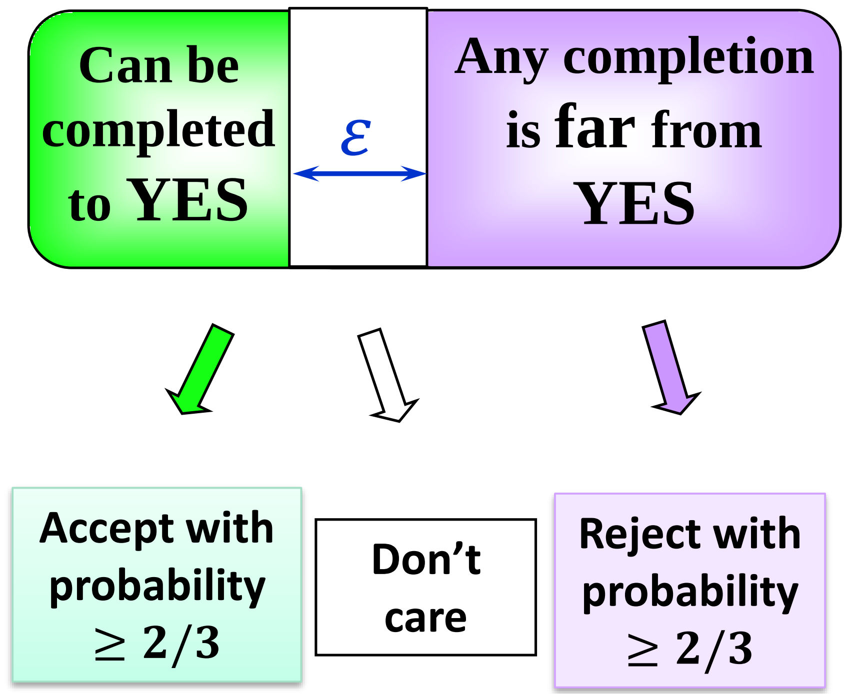
Property Testing with Erasures

Property Tester [Rubinfeld Sudan 96, Goldreich Goldwasser Ron 98]



Erasure-Resilient Property Tester [Dixit Raskhodnikova Thakurta Varma 16]

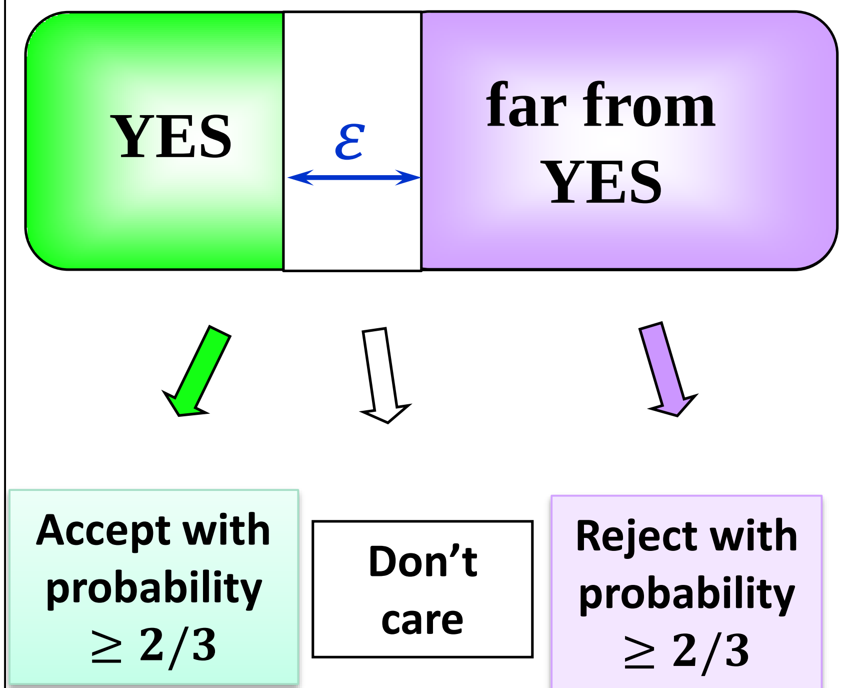
- $\leq \alpha$ fraction of the input is erased adversarially



Two objects are at distance ε = they differ in an ε fraction of places

Property Testing with Errors

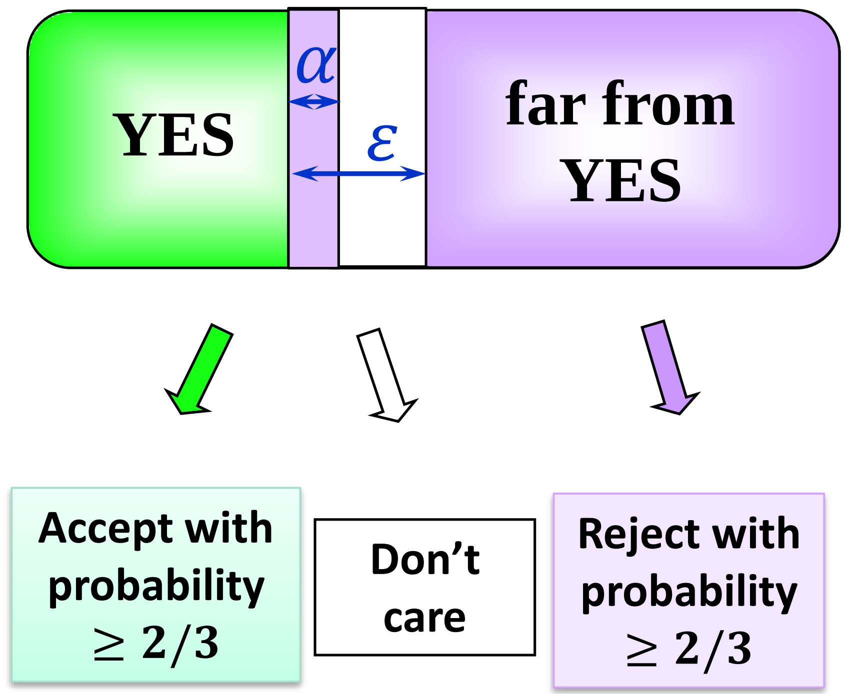
Property Tester [Rubinfeld Sudan 96, Goldreich Goldwasser Ron 98]



Tolerant Property Tester

[Parnas Ron Rubinfeld 06]

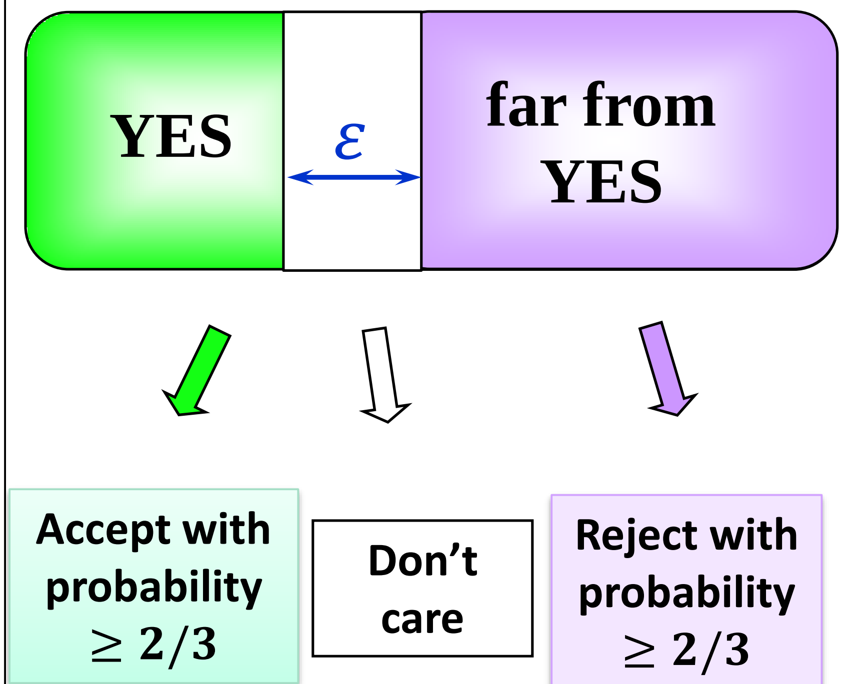
- $\leq \alpha$ fraction of the input is wrong



Two objects are at distance ε = they differ in an ε fraction of places

Property Testing with Errors

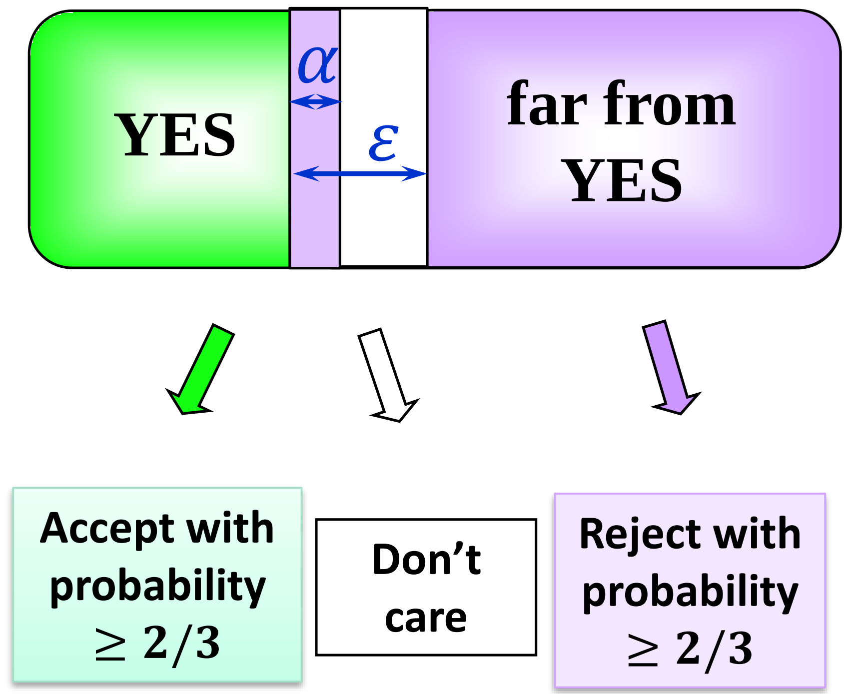
Property Tester [Rubinfeld Sudan 96, Goldreich Goldwasser Ron 98]



Tolerant Property Tester

[Parnas Ron Rubinfeld 06]

- $\leq \alpha$ fraction of the input is wrong

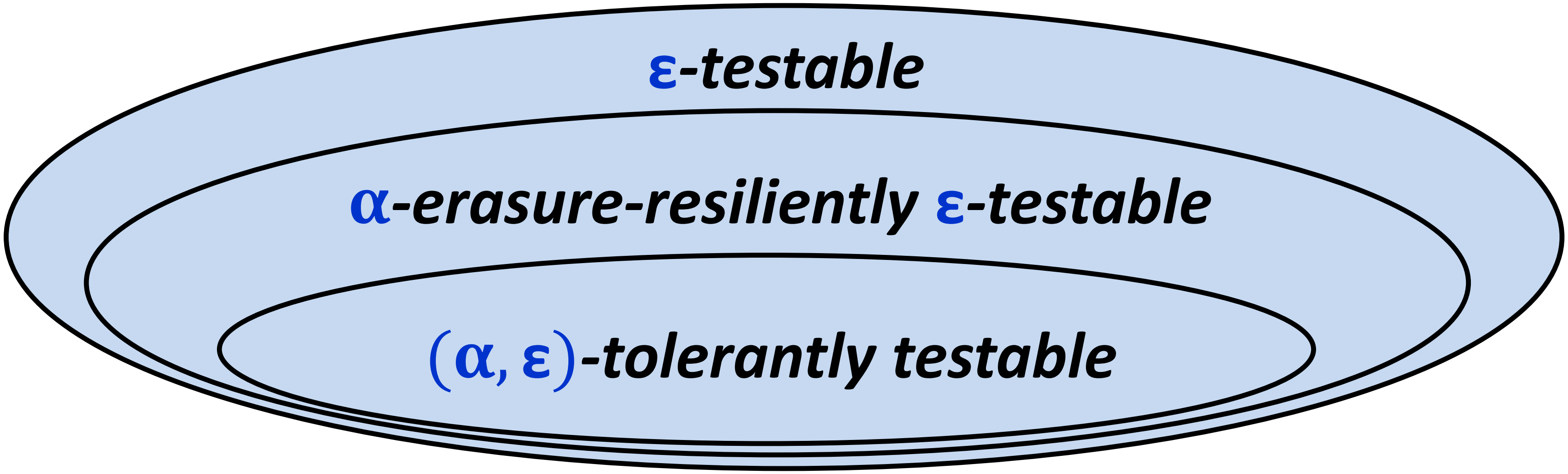


Two objects are at distance ε = they differ in an ε fraction of places

Relationships Between Models

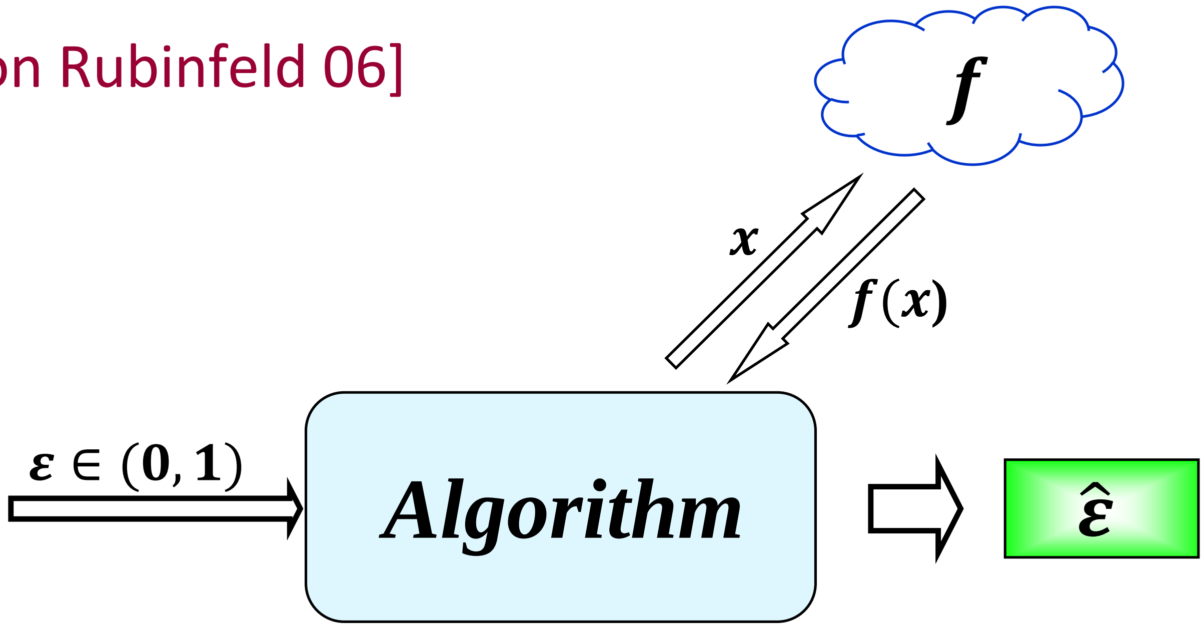
Containments are strict:

- [Fischer Fortnow 05]: standard vs. tolerant
- [Dixit **R** Thakurta Varma 16]: standard vs. erasure-resilient
- [**R** Ron-Zewi Varma 19]: erasure-resilient vs. tolerant



Distance Approximation for Boolean Functions

[Parnas Ron Rubinfeld 06]

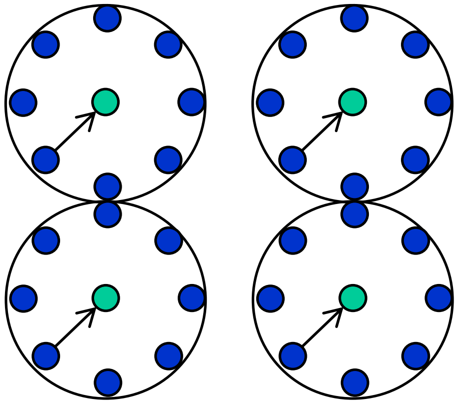


Goal: Output $dist(f, \mathcal{P}) \pm \varepsilon$

in sublinear time

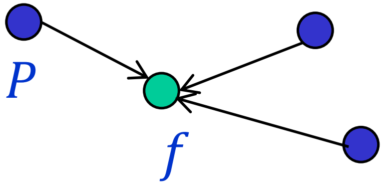
Sublinear-Time "Restoration" Models

Local Decoding



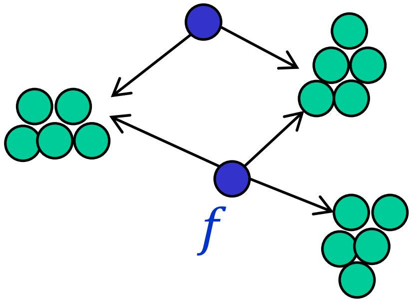
Input: A slightly corrupted codeword
Requirement: Recover individual bits of the closest codeword with a constant number of queries per recovered bit.

Program Checking



Input: A program P computing f correctly on most inputs.
Requirement: Self-correct program P: for a given input x, compute $f(x)$ by making a few calls to P.

Local Reconstruction



Input: Function f nearly satisfying some property P
Requirement: Reconstruct function f to ensure that the reconstructed function g satisfies P, changing f only when necessary. For each input x, compute $g(x)$ with a few queries to f.

Generalization: Local Computation

[Rubinfeld Tamir Vardi Xie 2011]

- Compute the i-th character y_i of a legal output y.
- If there are several legal outputs for a given input, be consistent with one.
- Example: maximal independent set in a graph.

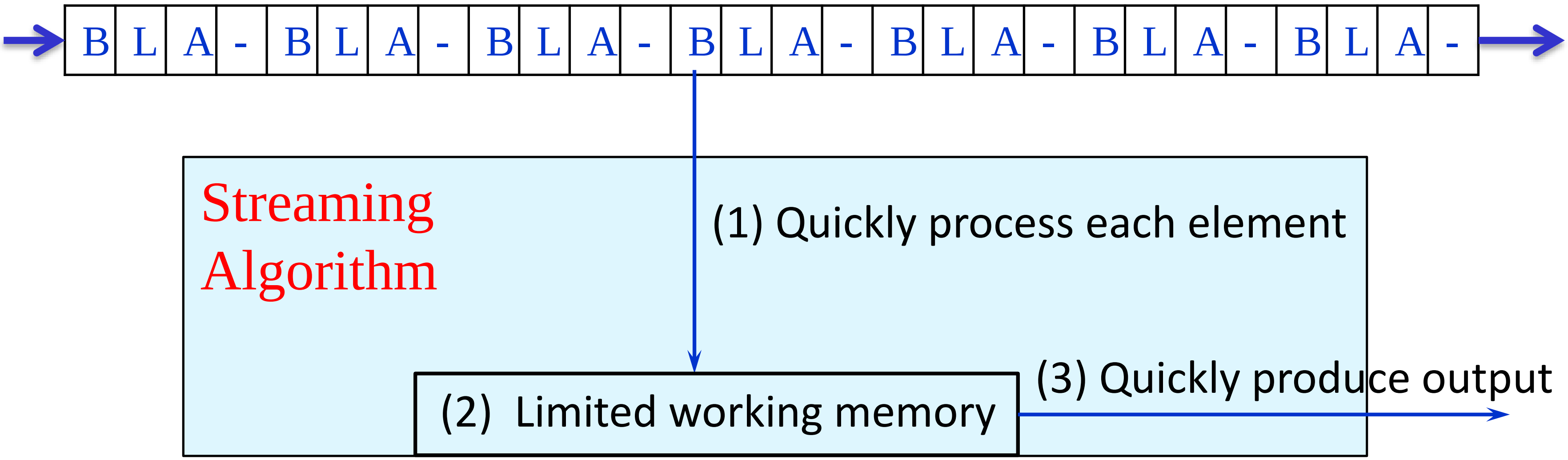
Sublinear-Space Algorithms

What if we cannot get a sublinear-time algorithm?

Can we at least get sublinear space?

Note: sublinear space is broader (for any algorithm, space complexity ≤ time complexity)

Data Stream Model



Motivation: internet traffic analysis

Model the stream as m elements from $[n]$, e.g.,

$$\langle x_1, x_2, \ldots, x_m \rangle = 3, 5, 3, 7, 5, 4, \ldots$$

Goal: Compute a function of the stream, e.g., median, number of distinct elements, longest increasing sequence.

Based on Andrew McGregor's slides: http://www.cs.umass.edu/~mcgregor/slides/10-jhu1.pdf

Streaming Puzzle

A stream contains $n - 1$ **distinct** elements from $[n]$ in arbitrary order.

Problem: Find the missing element, using $O(\log n)$ space.

Conclusion

Sublinear algorithms are possible in many settings

- simple algorithms, more involved analysis
- nice combinatorial problems
- unexpected connections to other areas
- many open questions

In the remainder of the course, we will cover research papers in the area.