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Contents

Group Testing: An Information Theory Perspective

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ABSTRACT

The group testing problem concerns discovering a small number of defective items within a large population by performing tests on pools of items. A test is positive if the pool contains at least one defective, and negative if it contains no defectives. This is a sparse inference problem with a combinatorial flavour, with applications in medical testing, biology, telecommunications, information technology, data science, and more.

In this monograph, we survey recent developments in the group testing problem from an information-theoretic perspective. We cover several related developments: efficient algorithms with practical storage and computation requirements, achievability bounds for optimal decoding methods, and algorithm-independent converse bounds. We assess the theoretical guarantees not only in terms of scaling laws, but also in terms of the constant factors, leading to the notion of the *rate* of group testing, indicating the amount of information learned per test. Considering both noiseless and noisy settings, we identify several regimes where existing algorithms are provably optimal or near-optimal, as

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well as regimes where there remains greater potential for improvement.

In addition, we survey results concerning a number of variations on the standard group testing problem, including partial recovery criteria, adaptive algorithms with a limited number of stages, constrained test designs, and sublinear-time algorithms.

Notation

n	number of items (Definition 1.1)
k	number of defective items (Definition 1.1)
$\mathcal{K}$	defective set (Definition 1.1)
$\mathbf{u} = (u_i)$	defectivity vector: $u_i = \mathbf{1}(i \in \mathcal{K})$, shows if item i is defective (Definition 1.2)
α	sparsity parameter in the sparse regime $k = \Theta(n^\alpha)$ (Remark 1.1)
β	sparsity parameter in the linear regime $k = \beta n$ (Remark 1.1)
T	number of tests (Definition 1.3)
$\mathsf{X} = (x_{ti})$	test design matrix: $x_{ti} = \mathtt{1}$ if item i is in test t; $x_{ti} = \mathtt{0}$ otherwise (Definition 1.3)
$\mathbf{y} = (y_t)$	test outcomes (Definition 1.4)
$\vee$	Boolean inclusive `OR` (Remark 1.2)
$\widehat{\mathcal{K}}$	estimate of the defective set (Definition 1.5)
$\mathbb{P}(\mathrm{err})$	average error probability (Definition 1.6)
$\mathbb{P}(\mathrm{suc})$	success probability $= 1 - \mathbb{P}(\mathrm{err})$ (Definition 1.6)
rate	$\log_2 \binom{n}{k}/T$ (Definition 1.7)
O, o, Θ	asymptotic ‘Big O’ notation

R	an achievable rate (Definition 1.8)
$\overline{R}$	maximum achievable rate (Definition 1.8)
$S(i)$	the support of column i (Definition 1.9)
$S(\mathcal{L})$	the union of supports $\bigcup_{i \in \mathcal{L}} S(i)$ (Definition 1.9)
q	proportion of defectives (Appendix to Chapter 1)
$\overline{k}$	average number of defectives (Appendix to Chapter 1)
p	parameter for Bernoulli designs: each item is in each test independently with probability p (Definition 2.2)
L	parameter for near-constant tests-per-item designs: each item is in L tests sampled randomly with replacement (Definition 2.3)
ν	test design parameter: for Bernoulli designs, $p = \nu/k$ (Definition 2.2); for near-constant tests-per-item designs, $L = \nu T/k$ (Definition 2.3)
$h(x)$	binary entropy function: $h(x) = -x \log_2 x - (1-x)\log_2(1-x)$ (Theorem 2.2)
$p(y \mid m, \ell)$	probability of observing outcome y from a test containing ℓ defective items and m items in total (Definition 3.1).
ρ, φ, ϑ, ξ	noise parameters in binary symmetric (Example 3.1), addition (Example 3.2), dilution/Z channel (Example 3.3, 3.4), and erasure (Example 3.5) models
$\overline{\theta}$, $\underline{\theta}$	threshold parameters in threshold group testing model (Example 3.6)
Δ	decoding parameter for NCOMP (Section 3.4)

γ	decoding parameter for separate decoding of items (Section 3.5) and information-theoretic decoder (Section 4.2)
C_{chan}	Shannon capacity of communication channel (Theorem 3.1)
$m^{(r)}_{i \to t}(u_i)$, $\widehat{m}^{(r)}_{t \to i}(u_i)$	item-to-test and test-to-item messages (Section 3.3)
$\mathcal{N}(i)$, $\mathcal{N}(t)$	neighbours of an item node and test node (Section 3.3)
$\mathsf{X}_{\mathcal{K}}$	submatrix of columns of X indexed by $\mathcal{K}$ (Section 4.2.2)
$\mathbf{X}_{\mathcal{K}}$	a single row of $\mathsf{X}_{\mathcal{K}}$ (Section 4.2.2)
$V = V(\mathbf{X}_{\mathcal{K}})$	random number of defective items in the test indicated by $\mathbf{X}$ (Section 4.2.2)
$P_{Y \mid V}$	observation distribution depending on the test design only through V (Equation (4.3))
S_0, S_1	partition of the defective set (Equation (4.4))
$\imath$	information density (Equation (4.6))
$\mathsf{X}_{0,\tau}$, $\mathsf{X}_{1,\tau}$	sub-matrices of X corresponding to (S_0, S_1) with $\lvert S_0 \rvert = \tau$ (Equation (4.14))
$\mathbf{X}_{0,\tau}$, $\mathbf{X}_{1,\tau}$	sub-vectors of $\mathbf{X}_{\mathcal{K}}$ corresponding to (S_0, S_1) with $\lvert S_0 \rvert = \tau$
I_τ	conditional mutual information $I(\mathbf{X}_{0,\tau}; Y \mid \mathbf{X}_{1,\tau})$ (Equation (4.16))

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