Applying combinatorial group testing to trust evaluation in a distributed computing model

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Acknowledgements

- This talk is based on research conducted by my (ex) PhD student Georgios Kalogridis.
- George recently completed a part-time PhD whilst employed at Toshiba Research Labs in Bristol.

Agenda

1. Agent systems and spy agents
2. The spy agent routing problem
3. A simple approach
4. Problems
5. Building in resilience
6. Multi-stage testing
7. Concluding remarks

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Mobile agent systems

- A **mobile agent** is an aggregation of software and data able to:
  - migrate (move) from one computer to another autonomously;
  - continue execution on destination computer.
- Motivation is to reduce need to communicate – autonomous agent could visit many sites before returning to originator with results.

Context

- Just one example of a distributed computing model.
- Of course, each host machine must be able to receive, execute, and forward mobile agents.
- Model has attracted considerable attention from researchers over last 10-15 years.
- Interesting problems relating to game theory, artificial intelligence, etc.

Example application

- One widely discussed possible application relates to e-commerce.
- A ‘shopping agent’ could be programmed with user requirements and then sent out to find the best deal on offer.
- It might:
  - return to originator and provide summary of deals on offer;
  - actually conclude the best deal autonomously, and then simply return details of deal to originator.

Trust issues

- Two major security/trust issues associated with mobile agents.
  1. **Malicious agents**: a malicious agent might try to subvert a visited host and/or learn about other agents.
  2. **Malicious hosts**: a malicious host might seek to learn originator secrets from agent code, or simply unfairly influence outcome of agent computations (e.g. by changing competitor offers in e-commerce example).

Malicious agents

- This threat arises in any mobile code scenario.
- Many possible solutions, including:
  - sandboxing (as in Java);
  - proof carrying code (code carries proof of its properties which can be verified before execution);
  - code signing;
  - ...

Malicious hosts

- As many authors have observed, fixing this problem is very difficult.
- Host has complete control over code.
- Possible solutions include:
  - code obfuscation;
  - homomorphic encryption (allowing computing on encrypted data);
  - use of trusted computing to provide guarantees over host behaviour.
- These measures are designed to prevent bad things occurring ...

Remote host assessment

- In practice, it is often impossible to completely prevent bad outcomes.
- One approach is to try to minimise risk by using ‘more trusted’ hosts.
- Idea underlying this talk is a possible method for remote host trust evaluation.
- Results from this evaluation could be used by a reputation management system.

Spy agents

- Idea of spy agents is to send out agents which look genuine but which are purely present to test hosts.
- Originator tests a set of hosts by sending out a number of spy agents and awaiting results.
- Spy agents must contain information which can be misused (incentive to misbehave).
- Misbehaviour must be detectable by originator.

Analysing results

- Assumption is that agent mishandling will be detected; not who did it, but which agents have been abused.
- That is, after sending out agents, each to a predetermined set of hosts, the originator will (eventually) receive a positive or negative indication for each agent, i.e. of whether or not it has been abused.
- Need to analyse these results to identify bad hosts.

E.g. – decoy email addresses

- Could equip each agent with a decoy email address which looks genuine (and has high entropy).
- Agent policy could require non-dissemination of email address.
- If email address receives spam, then this is evidence of agent abuse.

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Assumptions

- All hosts are bad or good.
- An approach to agent design and use has been chosen that guarantees:
  - if an agent **route** (i.e. set of hosts it visits) includes at least one bad host then it will yield a positive result;
  - if an agent route include no had hosts then it will yield a negative result.
- The order in which an agent visits hosts is immaterial.
- Malicious hosts do not collude.

Discussion

- These are very strong assumptions.
- Consider later in talk how they might be weakened.
- We are concerned with choosing a set of agent routes so that the malicious hosts can be uniquely identified, no matter how they are distributed.
- Clearly a combinatorial problem ...

Constraints

- Wish to minimise number of spy agents and also number of agents received by each host.
- However, also assume that agents with large route sets are better, as malicious hosts are more likely to misbehave.
- Sending a unique agent to each host is not acceptable (unacceptable risk of detection to host, and perhaps no incentive to misbehave).

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Group testing

- The underlying combinatorial problem has been well-studied under many guises.
- In **group testing** a population of items containing a small set of defectives is tested in order to identify the defectives.
- Items are pooled for testing; a group test reports ‘positive’ if the tested pool contains one or more defective elements, and reports ‘negative’ otherwise.

Sequential & non-adaptive testing

- Two main types of group testing (GT) schemes: sequential and non-adaptive.
  - **Sequential** schemes allow the selection of later tests to be based upon the outcomes of previous tests. (Fewer tests in general).
  - In a **non-adaptive** scheme, the set of tests is predetermined. (Allows parallelism).
- Sequential GT goes back almost 70 years (Dorfman ,1943).

Non-adaptive GT

- Range of non-adaptive GT constructions have been proposed based on block designs, superimposed codes, transversal designs, cover-free families, and other combinatorial designs.
- Recent survey of non-adaptive GT provided by Du and Hwang (2006).

Application to spy agents

- In most cases non-adaptive approach likely to be more fruitful, because:
  - possibility of parallelism (sending out multiple agents at same time);
  - need results in shortest possible time.
- Look at a simple example.
- Note need for decoding algorithm (given agent results, need a means to determine bad host).

Formalisation

- **Route design** is a triple (R, S, I), where:
  - R is set of agents,
  - S is a set of n hosts, and
  - I is an incidence relation between R and S, corresponding to an agent visiting a host).
- Identify R with points and S with blocks of a block design (rows and columns of an incidence matrix).

Notational abuse

- Will often think of as a row or column of an incidence matrix as a set, and will refer to ‘membership’ of a row or column.
- Will also take this further and refer to the **union** of columns or rows, with the ‘obvious’ meaning.
- My excuse? Well, I’m just a Computer Scientist, so I don’t know any better ...

Classifiers

- Call a route design a *d*-classifier if, given **exactly** *d* defective hosts, the outcome of the design can be used to identify all the defective (and honest) hosts.
- A route design is a *d*-classifier if, given **at most** *d* defective hosts, the outcome of the design can be used to identify all the defective (and honest) hosts.

Separable matrices

- Incidence matrix is *d*-separable if 'unions' of subsets of **exactly** *d* columns are all distinct.
- Incidence matrix is *d̲*-separable if 'unions' of subsets of **at most** *d* columns are all distinct.
- Route design is *d*/*d̲*-classifier if and only if incidence matrix is *d*/*d̲*-separable (Kautz and Singleton, 1964).

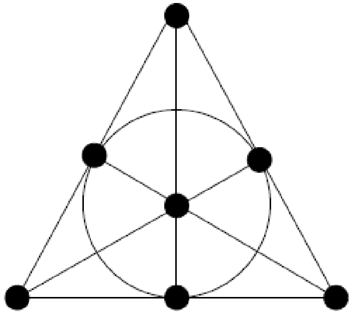
Decoding problem

- This solves the problem ...
- However, there is no efficient general decoding algorithm for separable schemes.
- (Decoding algorithm takes as input the outcome vector for all agents, and outputs the set of defective hosts).
- Hence look for restricted class, as follows.

Disjunct matrices

- Incidence matrix is *d*-disjunct if 'union' of any subset of **exactly** *d* columns does not contain any other column (as a 'subset').
- If matrix is *d*-disjunct, then it is:
  - *d′*-disjunct for all $d' \leq d$;
  - *d*-separable.
- Moreover, there is a simple decoding algorithm:
  - union of all negative rows (agents with negative outcomes) = set of all non-defective hosts.

Example



- Fano plane - a 2-(7,3,1) design.
  - 7 lines, 7 points;
  - 3 lines/point, 3 points/line;
  - 2 points on 1 line,
  - 2 lines intersect in 1 point

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}.$$

- Incidence matrix:
  - the incidence matrix for Fano plane is 2-disjunct but not 3-disjunct.

Example (continued)

- Decoding:
  - say the set of defectives is {2,5};
  - outcome vector is {1,1,0,1,1,0,1};
  - only columns that do not appear in negative routes are 2 and 5.

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Overly strong assumptions

- The assumptions we made are clearly very strong.
- Malicious hosts may not always misbehave.
- We need to develop techniques which work even when malicious hosts only selectively misbehave.

Reformulations

- We could assume that malicious hosts will behave in a more random manner.
- Group Testing techniques exist which can cope with errors, and such techniques might be appropriate in such an environment.
- We next consider a slightly different model, in which malicious hosts behave in ways to try to conceal their behaviour.

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A selective misbehaviour model

- We suppose a malicious host will only mishandle a visiting agent if it is scheduled to visit at least e-1 other malicious hosts, for some e>0;
  - such a malicious host is said to be of **type** e.
- We further suppose that type e (e>1) malicious hosts are aware of other hosts which are malicious.
- Clearly a type 1 malicious host will always mishandle a visiting agent.

Complex defectives

- To design sets of routes capable of dealing with scenarios where malicious hosts may be of varying types, we use the theory of **group testing for complexes** (GTC).
- GTC deals with identifying sets of objects that collectively (and minimally) yield a positive result.
- Such sets we call **defective complexes**.

Defective complexes – examples

- If there is a single malicious host of type 2, then set of defective complexes is empty.
- If there are two defective hosts of type 2, then the single defective complex will contain them both.
- If there are only two defective hosts, one of type 2 and one of type e (>2), then the single defective complex will contain them both.

Definition

- Given a set of hosts, a set of defective complexes is a collection *D* of subsets of hosts satisfying:
  1. an agent will give a positive result if and only if it contains a member of *D*;
  2. the previous property does not hold for a proper subset of *D*.
- Can show that the set of defective complexes is unique.
- Need to identify it ...

Separable matrices revisited

- The **rank** of a set of complex defectives is the size of the largest element.
- An incidence matrix is (d,e)-separable if, when applied to distinct sets of defective complexes of size at most d and rank e, distinct outcomes result.

Disjunct matrices revisited

- A route design is (d,e)-disjunct if, give any set of d+1 mutually non-inclusive complexes (sets of hosts) of rank e, then:
  - the set of agent routes containing all the hosts in the first complex, contains at least one agent route not containing any of the other complexes.
- (d,e)-disjunct implies (d,e)-separable (Du and Hwang, 2006).

Example

- The following (simple) route design is (2,2)-disjunct:

	c_1	c_2	c_3	c_4
r_1	1	1	0	0
r_2	1	0	1	0
r_3	1	0	0	1
r_4	0	1	1	0
r_5	0	1	0	1
r_6	0	0	1	1

Decoding

- Suppose a (d,e)-disjunct route design is applied to a set D of defective complexes with cardinality at most d and rank e.
- Determine D as follows:
  - Let E = set of all f-subsets of hosts, $f \leq e$.
  - Let G be elements of E (i.e. f-subsets of hosts) with property that every agent containing every host in the subset gives a positive result.
  - D = ‘minimal’ elements of G (i.e. those not containing another element of G as a subset).

Finding (*d*,*e*)-disjunct matrices

- A (*d*,*e*)-disjunct route design is equivalent to (see Chen, Du & Hwang, 2007):
  - a (*d*,*e*)-superimposed code;
  - a (*d*,*e*)-cover-free family, and
  - a (*d*,*e*)-key distribution pattern.
- Can construct such objects in many ways, e.g. using *t*-designs.

Identifying individual hosts

- So far we have considered identification of set of defective complexes.
- This must then be analysed to try to determine set of defective hosts.
- In general this will not be possible.
- For example, if there are *d* malicious hosts all with types greater than *d*, then no malicious host will ever misbehave.
- However, some special cases can be addressed.

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Adaptive group testing

- So far we have considered non-adaptive group testing.
- However, may be cases where adaptive (SGT) approach is more efficient.
- Unfortunately, ‘standard’ adaptive techniques don’t really work in our setting,
- This is because they typically involve doing tests for very small sets of hosts.

Definition – weak

- We wish to design schemes which never send agents to a very small set of hosts.
- Note that an adaptive scheme does not contain a single set of routes – the route set will vary depending on the results of earlier tests.
- In any scheme, a **weak** route is one with the smallest possible number of hosts for that scheme.

Optimality

- Suppose a SGT scheme *A* is capable of identifying all malicious hosts, regardless of their number.
- Let r_A be the length of a weak route in *A*.
- *A* is said to be **route-length-optimal** if, for any other scheme *B* which can identify all malicious hosts, $r_A \geq r_B$.

A result

- Suppose a set of n hosts is known to contain at most d malicious hosts.
- Then the length r of a weak route in an sequential scheme capable of detecting all malicious hosts satisfies $r \leq n-d$.

Meeting the bound

- A simple construction shows that the bound is tight.
- Essentially, conduct a series of rounds, and in round $i \geq 0$ send agents to every subset of $n-i$ hosts.
- Unfortunately, the route-length-optimal schemes involve sending large numbers of agents.
- Some sort of compromise is required ...

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Further work

- I have presented a combinatorial problem arising from a possible security mechanism for mobile agent systems.
- The solutions presented are all based on rather restrictive models of malicious host behaviour.
- Clearly, there is ample scope to develop schemes which correspond to less restricted models of behaviour.

Further information

- Much more information about this work is available in George's PhD thesis, which is available online:
  - G. Kalogridis, *Preemptive mobile code protection using spy agents*, Mathematics Department Technical Report **2012-04** (http://www.ma.rhul.ac.uk/static/techrep/2012/MA-2012-04.pdf).

Questions

- Questions ...

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