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

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Acknowledgements

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• 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 \textbf{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 \textbf{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 $d$-separable if ‘unions’ of subsets of at most $d$ columns are all distinct.

• Route design is $d/d$-classifier if and only if incidence matrix is $d/d$-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

- 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:

<table>
<thead>
<tr>
<th></th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$r_2$</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$r_3$</td>
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<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$r_4$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$r_5$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$r_6$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
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:
Questions

• Questions ...

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