Certification of Large Distributed Computations with Task Dependencies in Hostile Environments

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Presentation Outline

- **Motivation: Application and Threat**
- Execution Model
- Certification with independent tasks
- Certification with task dependencies
- Results
- Conclusions and Future Work

Target Application

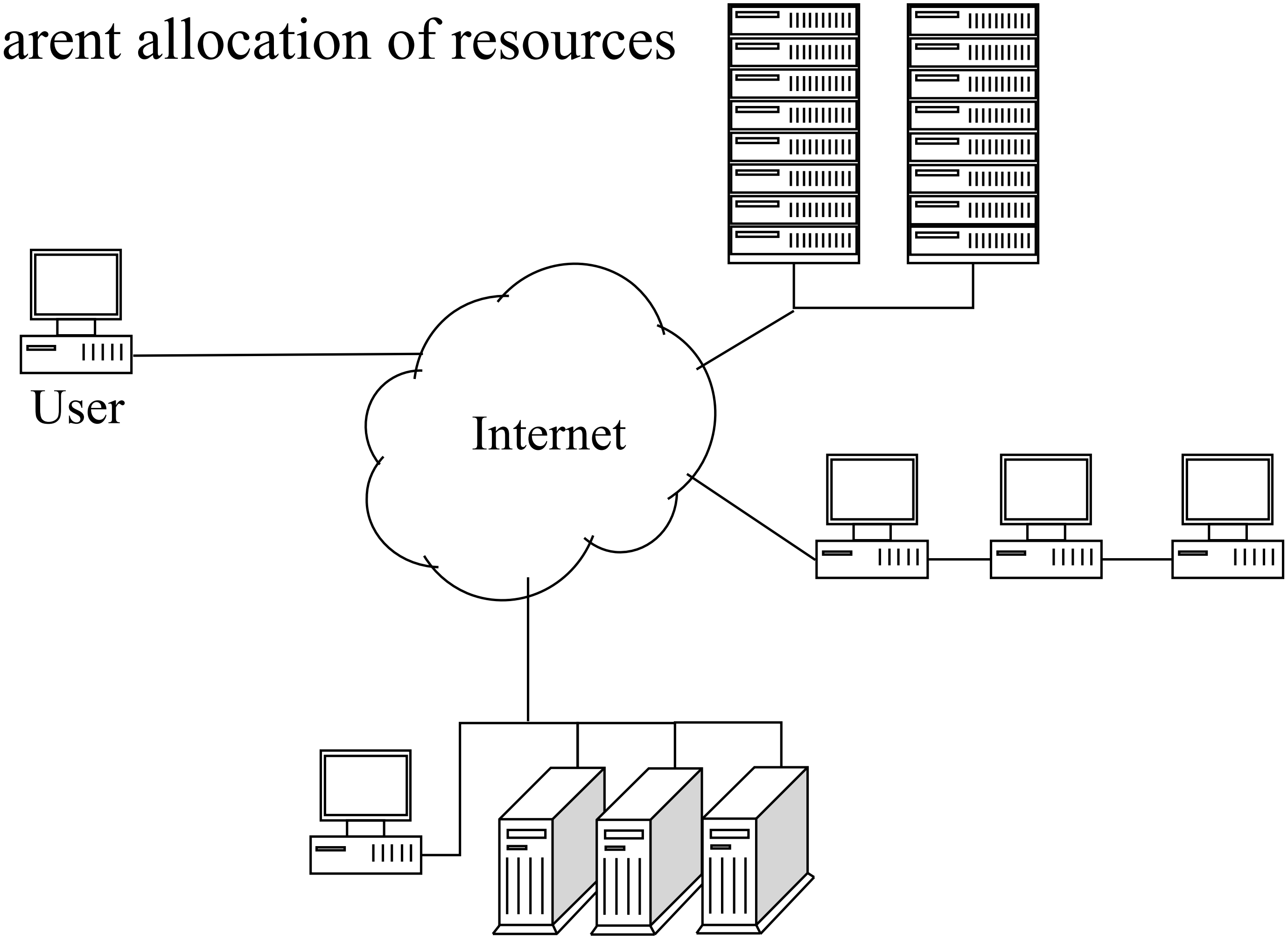
- Large-Scale Global Computing Systems

- Subject Application to Dependability Problems
  - Can be addressed in the design

- Subject Application to Security Problems
  - Requires solutions from the area of survivability, security, fault-tolerance

Global Computing Architecture

- Large-scale distributed systems (e.g. Grid, P2P)
- Transparent allocation of resources



Unbounded Environments

- In the Survivability Community our general computing environment is referred to as

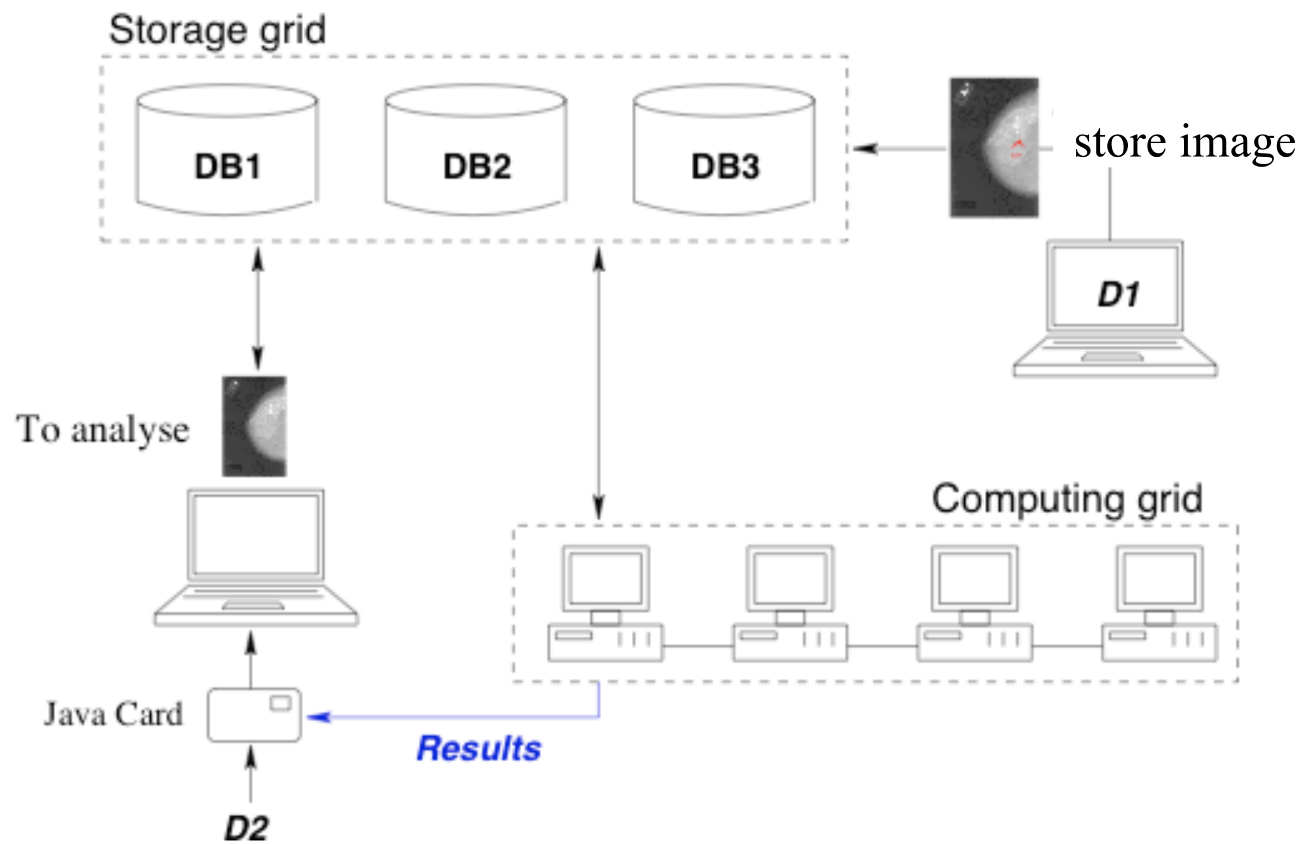
Unbounded Environment

  - Lack of physical / logical bound
  - Lack of global administrative view of the system.

What risks are we subjecting our applications to?

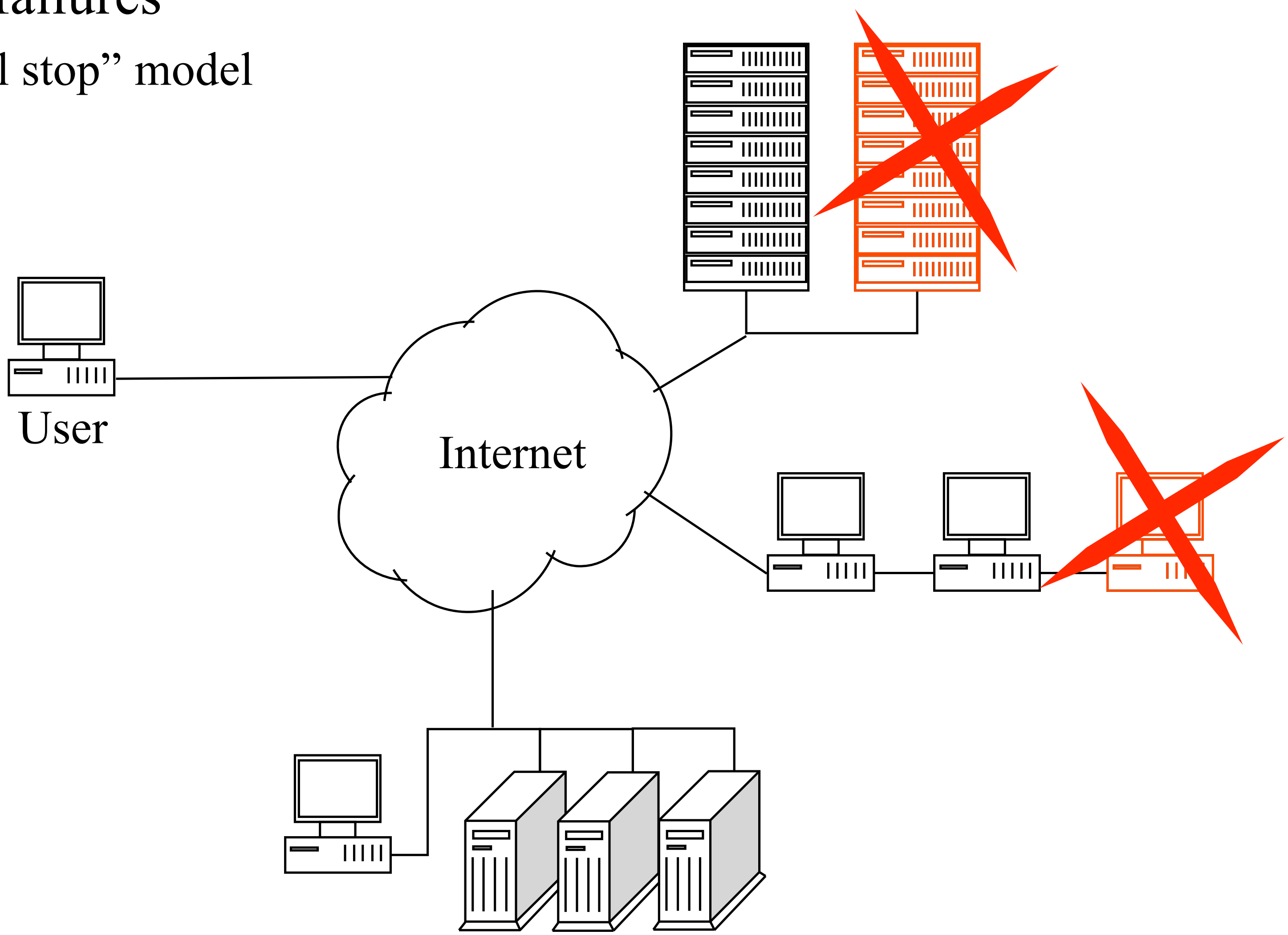
Typical Application

- Computation intensive parallel application
  - Medical (mammography comparison)



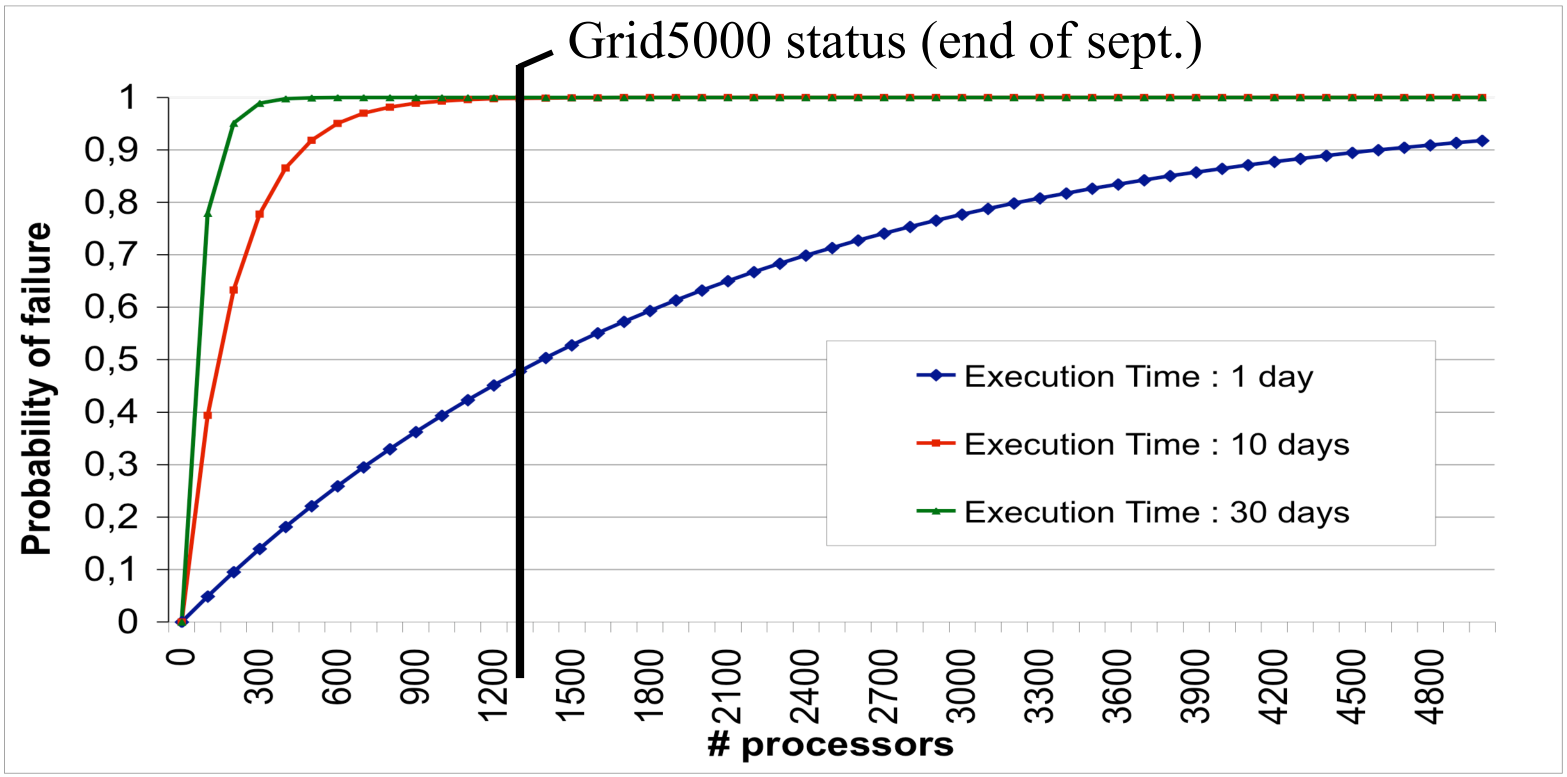
Two kinds of failures (1/2)

1. Node failures
   - "fail stop" model



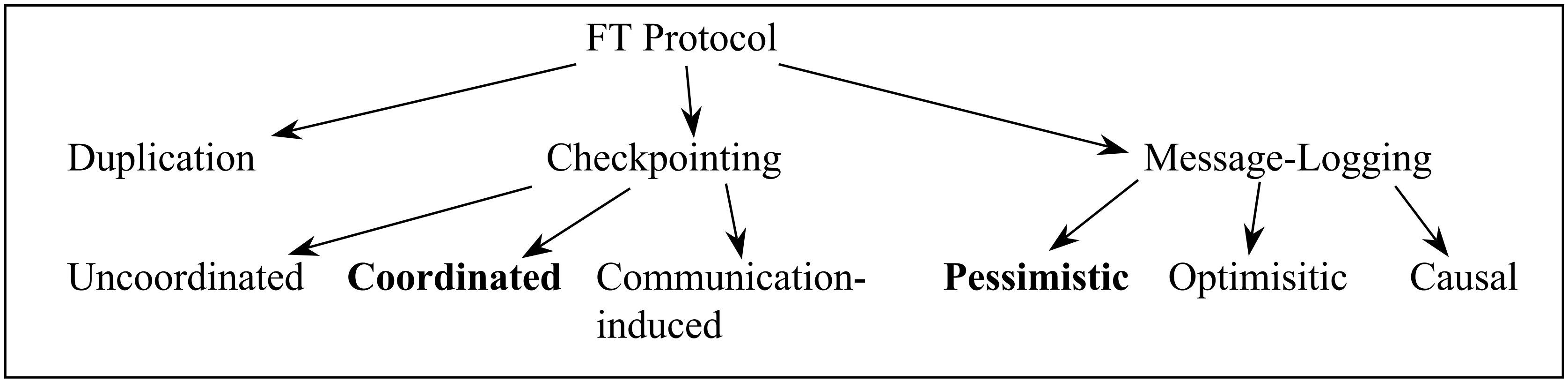
Unreliability in the absence of Fault Tolerance Mechanism

- Computation on Cluster
  - MTBF = 2000 days (48,000h, approx. 5 1/2 years)
  - Unreliability of one node: $F(t) = 1 - R(t) = 1 - e^{-\lambda t}$



Fault Tolerance Approaches

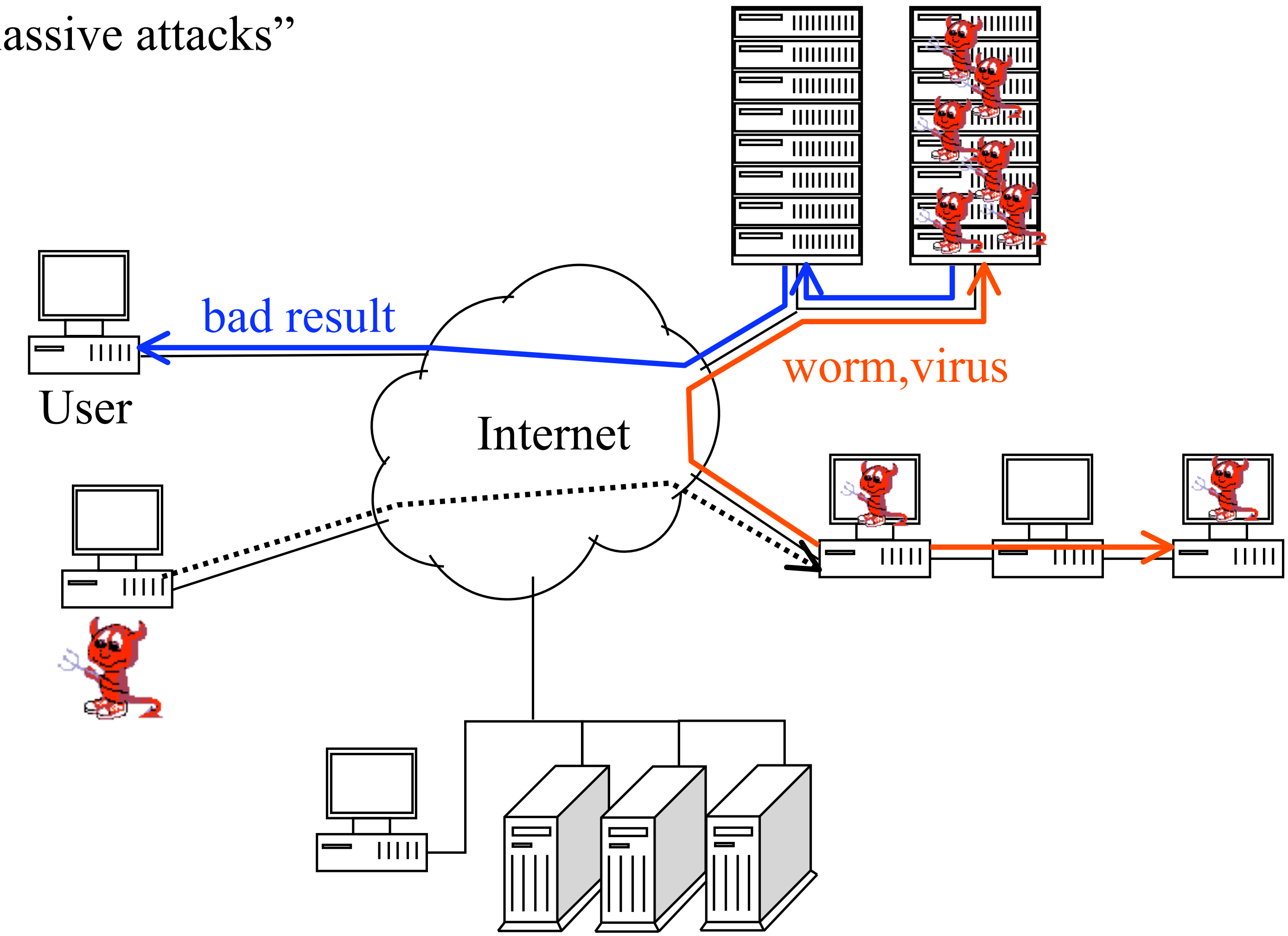
- Simplified Taxonomy for Fault Tolerance Protocols



- Rely on a "stable storage"
  - persistent and assumed to be reliable [Kaapi / Athapascan]
  - If not persistent: only duplication of saved data (checkpoint / message)
    - probabilistic FT protocols: fault tolerance is guaranteed with good probability

Two kinds of failures (2/2)

2. Task forgery
   – “massive attacks”



How bad is the Problem?

- Vulnerabilities reported (CERT/CC statistics)

1995-1999

Year	1995	1996	1997	1998	1999
Vulnerabilities	171	345	311	262	417

2000-2004

Year	2000	2001	2002	2003	2004
Vulnerabilities	1,090	2,437	4,129	3,784	3,780

Total vulnerabilities reported (1995-2004): **16,726**

How bad is the Problem?

- Incidents reported (CERT/CC statistics)

1988-1989

Year	1988	1989
Incidents	6	132

1990-1999

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Incidents	252	406	773	1,334	2,340	2,412	2,573	2,134	3,734	9,859

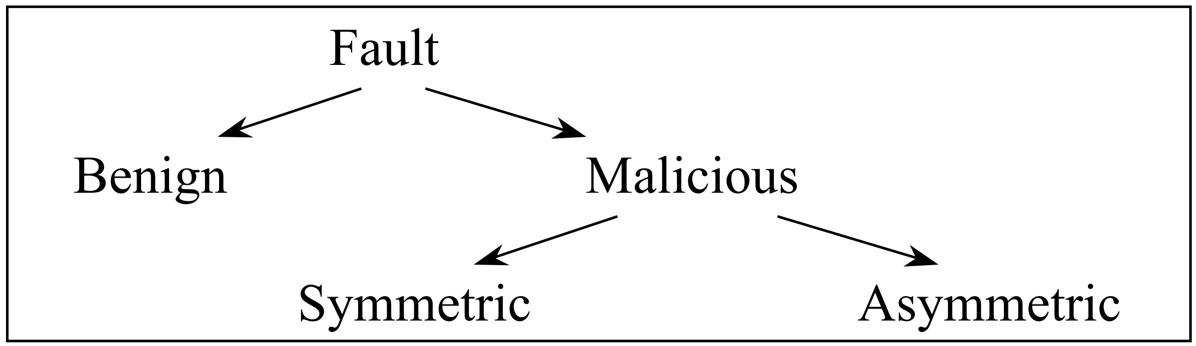
2000-2003

Year	2000	2001	2002	2003
Incidents	21,756	52,658	82,094	137,529

Total incidents reported (1988-2003): **319,992**

Fault Models

- Simplified Fault Taxonomy



- Fault-Behavior and Assumptions
  - Independence of faults
  - Common mode faults -> towards arbitrary faults!

- Fault Sources
  - Trojan, virus, DOS, etc.
  - How do faults affect the overall system?

Assumptions

- Anything is possible!
  - » and it <u>will</u> happen!
- Malicious act will occur sooner or later
- It is hard or impossible to predict the behavior of an attack

Attacks and their impact

- Attacks
  - single nodes, difficult to solve with certification strategies
  - solutions: e.g. intrusion detection systems (IDS)

- Massive Attacks
  - affects large number of nodes
  - may spread fast (worm, virus)
  - may be coordinated (Trojan)

- Impact of Attacks
  - attacks are likely to be widespread within neighborhood, e.g. subnet

- Our focus: massive attacks
  - virus, trojan, DoS, etc.

Certification Against Attacks

- Mainly addressed for **independent tasks**
- Current approaches
  - Simple checker [Blum97]
  - Voting [SETI@home]
  - Spot-checking [Germain-Playez 2003, based on Wald test]
  - Blacklisting
  - Credibility-based fault-tolerance [Sarmenta 2003]
  - Partial execution on reliable resources (partitioning) [Gao-Malewicz 2004]
  - Re-execution on reliable resources
- Certification of Computation

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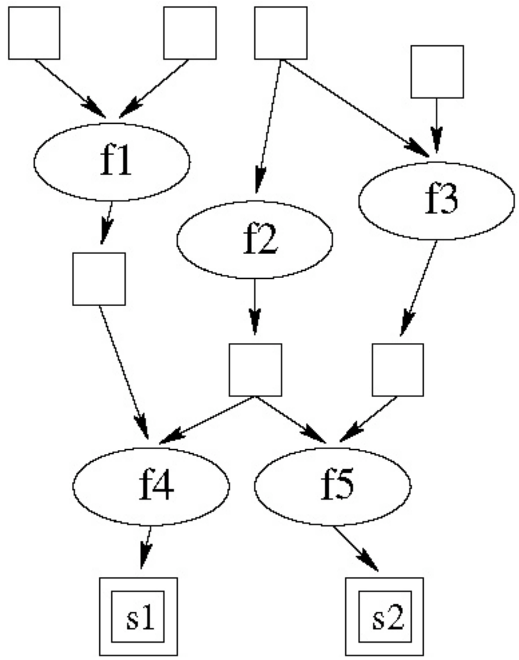
Definitions and Assumptions

- Dataflow Graph
  - $G = (\mathcal{V}, \mathcal{E})$

    $\mathcal{V}$ finite set of vertices v_i

    $\mathcal{E}$ set of edges e_{jk} vertices v_j , $v_k \in \mathcal{V}$



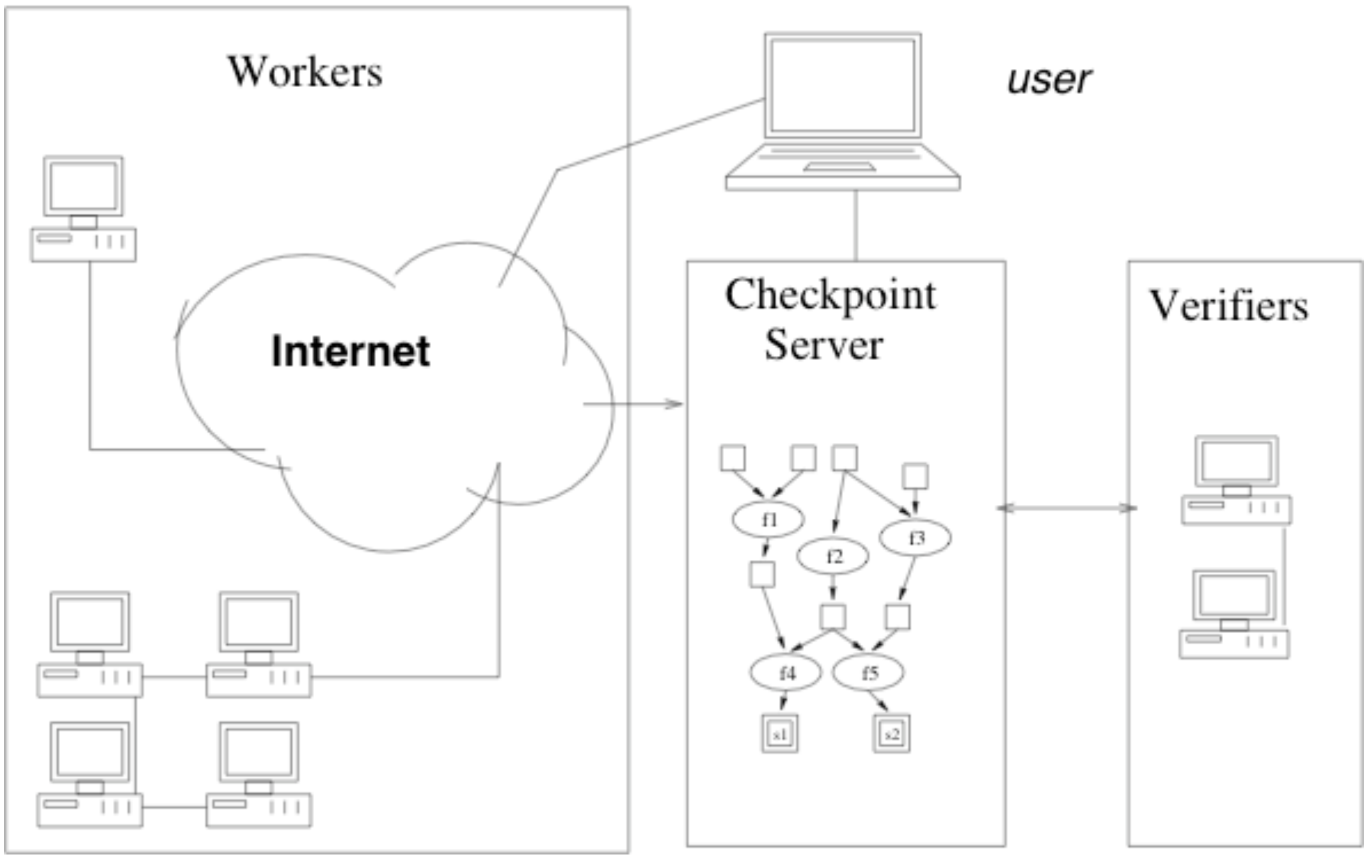
- Two kinds of tasks

  T_i Tasks
  in the traditional sense

  D_j Data tasks
  inputs and outputs

Global Computing Platform (GCP)

- GCP includes workers, checkpoint server and verifiers



Definitions

- Executions in unreliable environment

  E execution of workload represented by G

  $i(T,E)$ input to T in execution E

  $o(T,E)$ output of T in execution E

- Executions in reliable environment: Verifier

  $\hat{E}$ execution of workload G on Verifier

  $\hat{\imath}(T,\hat{E})$ input to T in execution $\hat{E}$

  $\hat{o}(T,\hat{E})$ output of T in execution $\hat{E}$

  $\hat{o}(T,E)$ output of T with input from E executing on verifier

  Note: notations $\hat{o}(T,\hat{E})$ and $\hat{o}(T,E)$ differ!

- If $E = \hat{E}$ then E is said to be "correct"

  otherwise E is said to have "failed"

Probabilistic Certification

- Monte Carlo certification: (analogy to Miller-Rabin)
  - a randomized algorithm that
    1. takes as input *E* and an arbitrary ε, $0 < \varepsilon \leq 1$
    2. delivers
       - either CORRECT
       - or FAILED, together with a proof that *E* has failed
  - certification is with error ε if the probability of answer CORRECT, when *E* has actually failed, is less than or equal to ε.

Probabilistic Certification

- What does the certification really mean?
  - what is the real interpretation of $E = \hat{E}$
  - connection between $E = \hat{E}$ and massive attack
  - use $E \neq \hat{E}$ as a "tool" to determine if a massive attack has occurred

- Monte Carlo certification against massive attacks
  - number of tasks actually failed/attacked n_F
  - consider two scenarios
    - » $n_F = 0$
    - » n_F is large => massive attack

- Attack Ratio q

$$n_q = \lceil nq \rceil \leq n_F$$

Monte Carlo Test

- Algorithm MCT

1. Uniformly select one task T in G
   we know input $i(T,E)$ and output $o(T,E)$ of T from checkpoint server
2. Re-execute T on verifier, using $i(T,E)$ as inputs, to get output $\hat{o}(T,E)$
   If $o(T,E) \neq \hat{o}(T,E)$ return FAILED
3. Return CORRECT

Certification of Independent Tasks

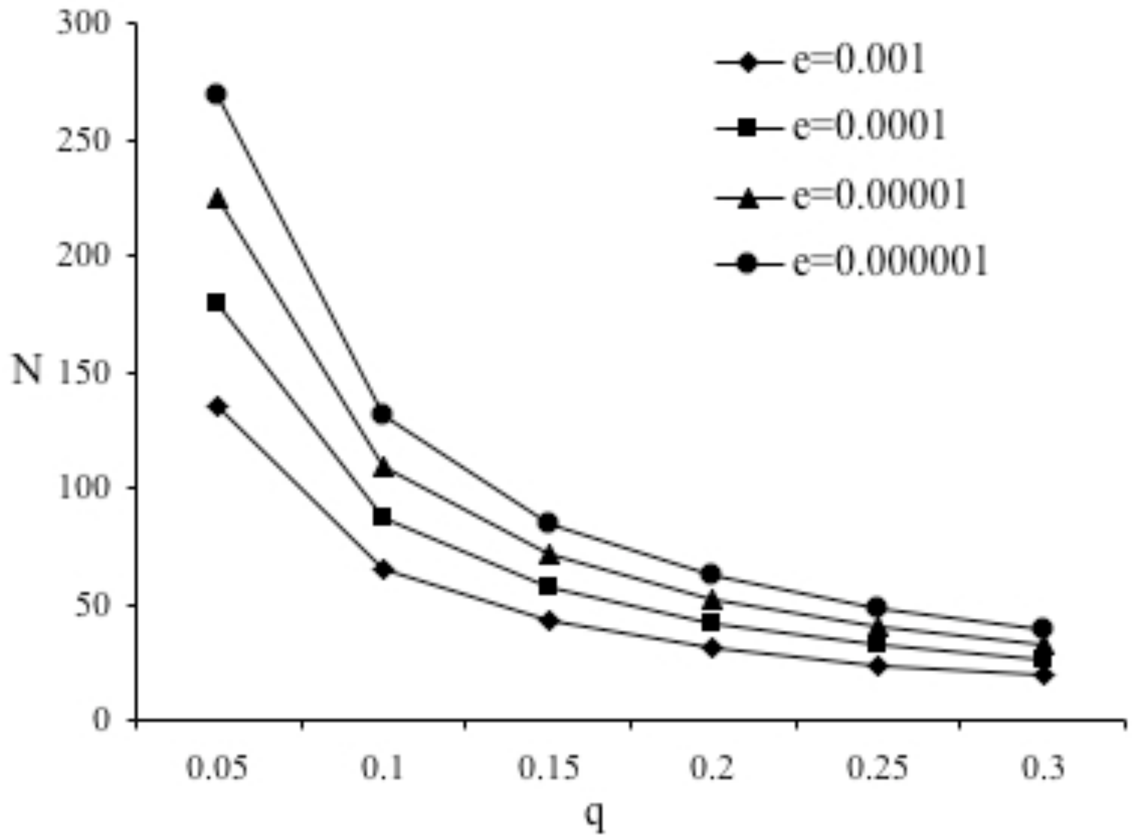
- How many independent executions of MCT are necessary to achieve certification of E with probability of error $\leq \varepsilon$?

$$N \geq \left\lceil \frac{\log \varepsilon}{\log(1-q)} \right\rceil$$

  - Prob. that MCT selects a non-forged tasks is $\dfrac{n - n_F}{n} \leq 1 - q$
  - N independent applications of MCT results in $\varepsilon \leq (1 - q)^N$

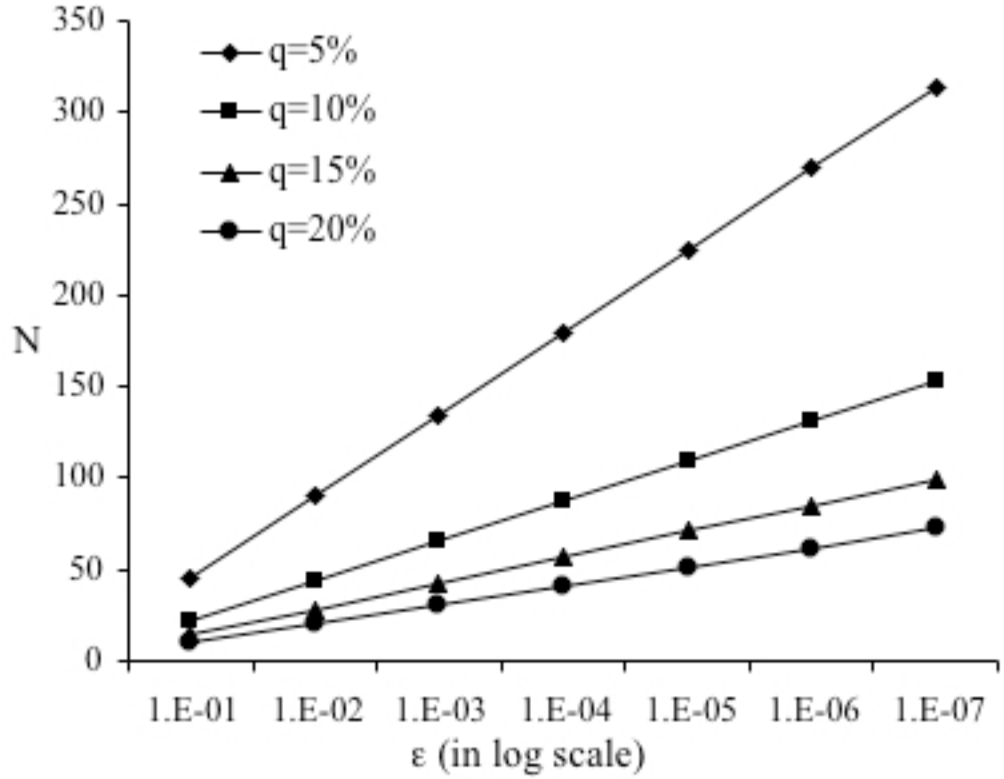
Certification of Independent Tasks

- Relationship between attack ratio and N



Certification of Independent Tasks

- Relationship between certification error and N



For q = 1% :

•300 checks => $\varepsilon < 5\%$

•4611 checks => $\varepsilon < 10^{-20}$

•24000 checks => $\varepsilon < 10^{-125}$

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Certification and Task Dependencies

- What does a re-execution really tell us w.r.t. the result?
  - One can only talk about outputs of tasks, not tasks!
  - If $o(T,E) \neq \hat{o}(T,E)$ we know that an error has occurred
  - If $o(T,E) = \hat{o}(T,E)$ we cannot say much at all!
    - for independent tasks this indicated a good task/result
    - what do we know about the inputs?
      - in the presence of error propagation -- not much!
    - if the verifier uses $\hat{\imath}(T,\hat{E})$ then $o(T,E) = \hat{o}(T,\hat{E})$ indicates a good result but we don't have $\hat{E}$, (would require total re-execution on verifier)

Certification and Task Dependencies

- The concept of "Initiator"
  - $o(T,E) = \hat{o}(T,E)$ is only useful if we know that the inputs are correct
    - this implies that T has no forged predecessors
  - Definition:

    An ***initiator*** is a falsified tasks that has no falsified predecessors
  - Worst case assumption is very conservative
    - one still might detect a falsified non-initiator
    - but there is no guarantee

Certification and Task Dependencies

- Certification is now based on initiators
- Using Algorithm MCT we get

$$N \geq \left\lceil \frac{\log \varepsilon}{\log(1 - \frac{n_I}{n})} \right\rceil$$

Certification and Task Dependencies

$G^{\leq}(V)$	predecessor graph of all tasks in V
$k \leq n_F$	be the number of falsified tasks assumed
$I(F)$	set of all initiators

- Minimum Number of Initiators

$$\gamma_V(k) = \min | G^{\leq}(V) \cap I(F) |$$

- Minimal Initiator Ratio

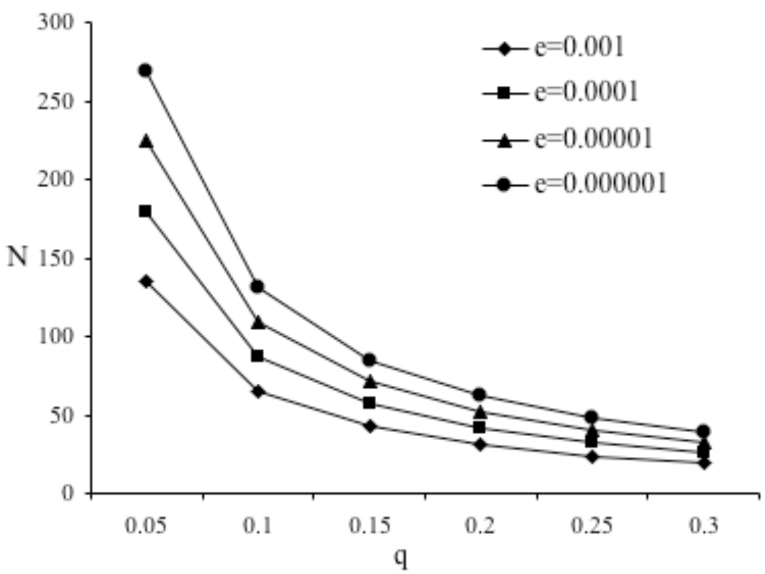
$$\Gamma_V(k) = \frac{\gamma_V(k)}{| G^{\leq}(V) |}$$

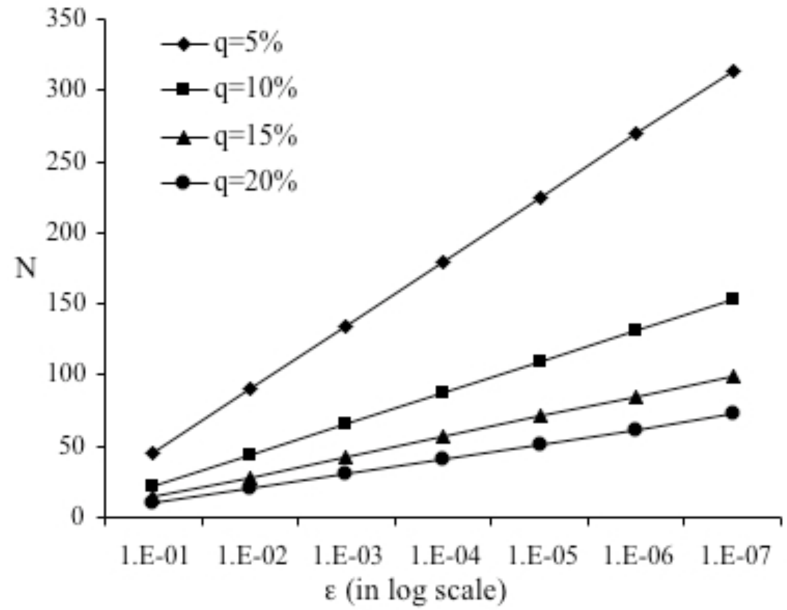
Extended Monte Carlo Test

- Algorithm EMCT
  1. Uniformly select one task T in G
  2. Re-execute all T_j in $G^{\leq}(T)$, which have not been verified yet, with input $i(T,E)$ on a verifier and return FAILED if for any T_j we have $o(T_j,E) \neq \hat{o}(T_j,E)$
  3. Return CORRECT
- Behavior
  - disadvantage: the entire predecessor graph needs to be re-executed
  - however: the cost depends on the graph
    - luckily our application graphs are mainly trees

Analysis of EMCT

- Results of independent tasks still hold,
  - but N hides the cost of verification
    - independent tasks: C = 1
    - dependent tasks: C = $|G^{\leq}(T)|$





Reducing the cost of verification

For EMCT the entire predecessor graph had to be verified
To reduce verification cost two approaches are considered next:

1. Verification with fractions of $G^{\leq}(T)$
2. Verification with fixed number of tasks in $G^{\leq}(T)$

Verifying with fractions of $G^{\leq}(T)$

- Algorithm EMCTα(E)

1. Uniformly choose one task T in G.
2. Uniformly select $n_\alpha = \lceil \alpha |G^{\leq}(T)| \rceil$ tasks in $G^{\leq}(T)$ and let this set be denoted by A. If for any $T_j \in A$, that has not been verified yet, re-execution on a verifier results in $\hat{o}(T_j, E) \neq o(T_j, E)$ then return FAILED.
3. Return CORRECT.

Verifying with fractions of $G^{\leq}(T)$

- For Algorithm EMCTα(*E*)

Lemma 1 *Let* T *be a task randomly chosen by* $EMCT_{\alpha}(E)$. *Then the probability of error,* e_{α}, *when* $EMCT_{\alpha}(E)$ *returns CORRECT is given by*

$$e_{\alpha} \leq \begin{cases} (1 - q\alpha\Gamma_T(n_q)) & \textit{for} \quad 0 < \alpha \leq 1 - \Gamma_T(n_q) \\ (1 - q) & \quad \quad \quad \quad \quad otherwise. \end{cases}$$

Verifying with fractions of $G^{\leq}(T)$

- For Algorithm EMCTα(*E*)

Theorem 1 *Let E be an execution with dependencies that is either correct or massively attacked with ratio q. Given ϵ and $0 < \alpha \leq 1$, N independent invocations of Algorithm $EMCT_{\alpha}(E)$ provide a certification with error probability*

$$\epsilon \leq \begin{cases} (1 - q\alpha\Gamma_G(n_q))^N & for\ 0 < \alpha \leq 1 - \Gamma_T(n_q) \\ (1-q)^N & otherwise. \end{cases}$$

Verifying fixed numbers of tasks

- We will now modify algorithm EMCT so that only a fixed number of tasks in the predecessors are verified.
  - We limit our investigations to unity, i.e. one task is verified.

Verifying fixed numbers of tasks

- Algorithm EMCT[1](E)

1. Uniformly choose one task T in G.
2. Uniformly select a single T_j in $G^{\leq}(T)$. If re-execution of T_j on a verifier results in $\hat{o}(T_j, E) \neq o(T_j, E)$ then return FAILED.
3. Return CORRECT.

Verifying fixed numbers of tasks

- For Algorithm $\mathrm{EMCT}^1(E)$

Lemma 2 *Let T be a task randomly chosen by $EMCT^1(E)$ and let $V = G^{\leq}(T)$. Then the probability of error, e_1, when $EMCT^1(E)$ returns CORRECT is given by*

$$e_1 \leq 1 - \frac{n_F}{n}\Gamma_T(n_F) \leq 1 - q\Gamma_T(n_q)$$

Verifying fixed numbers of tasks

- For Algorithm EMCT^1(*E*)

Theorem 2 *Let E be an execution with dependencies that is either correct or massively attacked with ratio q. Given ϵ then N independent invocations of Algorithm $EMCT^1(E)$ provide a certification with error probability*

$$\epsilon \leq (1 - q\Gamma_G(n_q))^N.$$

The cost of certification

- A balance between N and C

- Monte Carlo certification for a given ε:
  1. a priori convergence
     - determine up front how many times one has to verify
     - one does not know which tasks are selected
  2. run-time convergence
     - run until certain ε is achieved
     - take advantage of knowledge about task selected

  3. for general graphs
  4. for special graphs (e.g. out-trees)

Note: For independent tasks a priori and run-time convergence are the same.

Results for pathological cases

- Number of effective initiators
  - this is the # of initiators as perceived by the algorithm
  - e.g. for EMCT an initiator in $G^{\leq}(T)$ is <u>always</u> found, if it exists

	$MCT(E)$ [7]	$EMCT(E)$ [7]	$EMCT_{\alpha}(E)$	$EMCT^{1}(E)$
# of effective initiators	$\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$	n_q	$n_q \alpha \Gamma_T(n_q)$ or n_q	$n_q \Gamma_T(n_q)$
Probability of error	$1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	$1-q$	$1 - q\alpha\Gamma_T(n_q)$ or $1-q$	$1 - q\Gamma_T(n_q)$
A priori convergence	$\frac{\log \epsilon}{\log\left(1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}\right)}$	$\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\alpha\Gamma_G(n_q))}$ or $\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\Gamma_G(n_q))}$
q_e a priori	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_G(n_q)$ or q	$q\Gamma_G(n_q)$
q_e run-time	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_T(n_q)$ or q	$q\Gamma_T(n_q)$
Verification cost (exact)	1	$\lvert G^{\leq}(T)\rvert$	$\lceil \alpha \lvert G^{\leq}(T)\rvert \rceil$	1
Max. cost (out-tree)	1	h	αh	1

Results for pathological cases

- Probability of error induced by one invocation
  - derived for each algorithm

	$MCT(E)$ [7]	$EMCT(E)$ [7]	$EMCT_\alpha(E)$	$EMCT^1(E)$
# of effective initiators	$\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$	n_q	$n_q\alpha\Gamma_T(n_q)$ or n_q	$n_q\Gamma_T(n_q)$
Probability of error	$1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	$1-q$	$1-q\alpha\Gamma_T(n_q)$ or $1-q$	$1-q\Gamma_T(n_q)$
A priori convergence	$\frac{\log\epsilon}{\log\left(1-\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}\right)}$	$\frac{\log\epsilon}{\log(1-q)}$	$\frac{\log\epsilon}{\log(1-q\alpha\Gamma_G(n_q))}$ or $\frac{\log\epsilon}{\log(1-q)}$	$\frac{\log\epsilon}{\log(1-q\Gamma_G(n_q))}$
q_e a priori	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_G(n_q)$ or q	$q\Gamma_G(n_q)$
q_e run-time	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_T(n_q)$ or q	$q\Gamma_T(n_q)$
Verification cost (exact)	1	$\lvert G^{\leq}(T)\rvert$	$\lceil\alpha\lvert G^{\leq}(T)\rvert\rceil$	1
Max. cost (out-tree)	1	h	αh	1

Results for pathological cases

- A priori convergence (N is determined a priori)
  - cannot take advantage of run-time knowledge
  - has to use $\Gamma_G(n_q)$ rather than $\Gamma_T(n_q)$
  - q_e is the effective attack ratio

$$N \geq \left\lceil \frac{\log \varepsilon}{\log(1 - q_e)} \right\rceil$$

	$MCT(E)$ [7]	$EMCT(E)$ [7]	$EMCT_\alpha(E)$	$EMCT^1(E)$
# of effective initiators	$\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$	n_q	$n_q \alpha \Gamma_T(n_q)$ or n_q	$n_q \Gamma_T(n_q)$
Probability of error	$1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	$1 - q$	$1 - q\alpha\Gamma_T(n_q)$ or $1 - q$	$1 - q\Gamma_T(n_q)$
A priori convergence	$\frac{\log \epsilon}{\log\left(1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}\right)}$	$\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\alpha\Gamma_G(n_q))}$ or $\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\Gamma_G(n_q))}$
q_e a priori	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_G(n_q)$ or q	$q\Gamma_G(n_q)$
q_e run-time	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_T(n_q)$ or q	$q\Gamma_T(n_q)$
Verification cost (exact)	1	$\lvert G^{\leq}(T) \rvert$	$\lceil \alpha \lvert G^{\leq}(T) \rvert \rceil$	1
Max. cost (out-tree)	1	h	αh	1

Results for pathological cases

- Run-time convergence (*N* is determined at run-time)
  - takes advantage of run-time knowledge
  - initial verification $\varepsilon_e = 1 - q_e$
  - each verification $\varepsilon_e = \varepsilon_e (1 - q_e)$
  - until $\varepsilon_e \leq \varepsilon$

$$N \geq \left\lceil \frac{\log \varepsilon}{\log(1 - q_e)} \right\rceil$$

	$MCT(E)$ [7]	$EMCT(E)$ [7]	$EMCT_\alpha(E)$	$EMCT^1(E)$
# of effective initiators	$\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$	n_q	$n_q \alpha \Gamma_T(n_q)$ or n_q	$n_q \Gamma_T(n_q)$
Probability of error	$1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	$1 - q$	$1 - q\alpha\Gamma_T(n_q)$ or $1 - q$	$1 - q\Gamma_T(n_q)$
A priori convergence	$\frac{\log \epsilon}{\log\left(1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}\right)}$	$\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\alpha\Gamma_G(n_q))}$ or $\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\Gamma_G(n_q))}$
q_e a priori	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_G(n_q)$ or q	$q\Gamma_G(n_q)$
q_e run-time	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_T(n_q)$ or q	$q\Gamma_T(n_q)$
Verification cost (exact)	1	$\lvert G^{\leq}(T) \rvert$	$\lceil \alpha \lvert G^{\leq}(T) \rvert \rceil$	1
Max. cost (out-tree)	1	h	αh	1

Results for pathological cases

- Verification cost
  - per invocation of the algorithm
  - special case: out-tree

	$MCT(E)$ [7]	$EMCT(E)$ [7]	$EMCT_\alpha(E)$	$EMCT^1(E)$
# of effective initiators	$\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$	n_q	$n_q \alpha \Gamma_T(n_q)$ or n_q	$n_q \Gamma_T(n_q)$
Probability of error	$1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	$1 - q$	$1 - q\alpha\Gamma_T(n_q)$ or $1 - q$	$1 - q\Gamma_T(n_q)$
A priori convergence	$\frac{\log \epsilon}{\log\left(1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}\right)}$	$\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\alpha\Gamma_G(n_q))}$ or $\frac{\log \epsilon}{\log(1-q)}$	$\frac{\log \epsilon}{\log(1-q\Gamma_G(n_q))}$
q_e a priori	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_G(n_q)$ or q	$q\Gamma_G(n_q)$
q_e run-time	$\frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	q	$q\alpha\Gamma_T(n_q)$ or q	$q\Gamma_T(n_q)$
Verification cost (exact)	1	$\lvert G^{\leq}(T)\rvert$	$\lceil \alpha \lvert G^{\leq}(T)\rvert \rceil$	1
Max. cost (out-tree)	1	h	αh	1

Conclusions

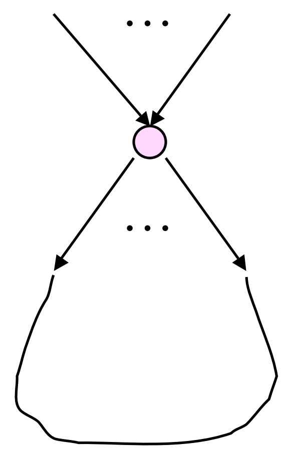
- Certification of large distributed applications
  - hostile environments with no assumptions on fault model
- Considered task dependencies
  - tasks or data may be manipulated
  - allows for error propagation (much more difficult than independent case)
  - very difficult to speculate on the behavior of a falsified task
- Several probabilistic certification algorithms were introduced
  - based on re-execution on verifier (reliable resource)
  - inputs available from dataflow checkpoints
- Certification:
  - very low probability of error can be achieved
  - number of tasks to verify is relatively small, depending on graph
  - relationship between attack rate and probability of error

Questions?

Certification and Task Dependencies

- The impact of graph *G*
  - Knowing the graph, an attacker may attempt to minimize the visibility of even a massive attack with ration *q*.
  - What is the number of initiators one might have to expect in a graph?
    - In the worst case we have

$$\gamma_G(n_F) = \left\lceil \frac{n_F}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$$



Results for MCT and EMTC

- Considered
  - General graphs
  - Out-trees (application domain based on out/in-trees)

Algorithm	MCT	$EMCT$
Number of effective initiators	$\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil$	n_q
Probability of error	$1 - \frac{\left\lceil \frac{n_q}{\left(\frac{1-d^h}{1-d}\right)} \right\rceil}{n}$	$1 - q$
Verification cost: general G	1	$O(n)$
Verification cost: G is out-tree	1	$h - log_d(n_v)$
Ave. # effective initiators, G is out-tree	$\left\lceil \frac{n_q}{\left(\frac{1-(h+2)d^{h+1}+(h+1)d^{h+2}}{(1-d)(1-d^{h+1})}\right)} \right\rceil$	n_q

Relationship between quantities

- Given a subset V of tasks in G.

  What are the relationships between

  $\gamma_V(k)$, $\gamma_G(k)$ and n_I with respect to $k = n_q$ or $k = n_F$?

  By definition

  $q \le n_F / n$ and thus $n_q \le n_F$

  also

  $n_I \le n_F$

Relationship between quantities

- With respect to n_F we always have

  $$\gamma_V(n_F) \le \gamma_G(n_F) \le n_I \le n_F$$

  - But where does n_q fit into this inequality?
  - The only certain relationship is $n_q \le n_F$

- With respect to n_q we always have

  $$\gamma_V(n_q) \le \gamma_G(n_q) \le n_q \le n_F$$

  - But where does n_I fit into this inequality?
  - The only certain relationship is $\gamma_G(n_q) \le n_I \le n_F$

Relationship between quantities

- With respect to $n_q \leq n_F$ we can compare directly

$$\gamma_{\mathrm{V}}(n_q) \leq \gamma_{\mathrm{V}}(n_F)$$
$$\gamma_{\mathrm{G}}(n_q) \leq \gamma_{\mathrm{G}}(n_F)$$

Thus

$$\Gamma_{\mathrm{V}}(n_q) \leq \Gamma_{\mathrm{V}}(n_F)$$
$$\Gamma_{\mathrm{G}}(n_q) \leq \Gamma_{\mathrm{G}}(n_F)$$