Timing Attacks for Recovering Private Entries From Database Engines

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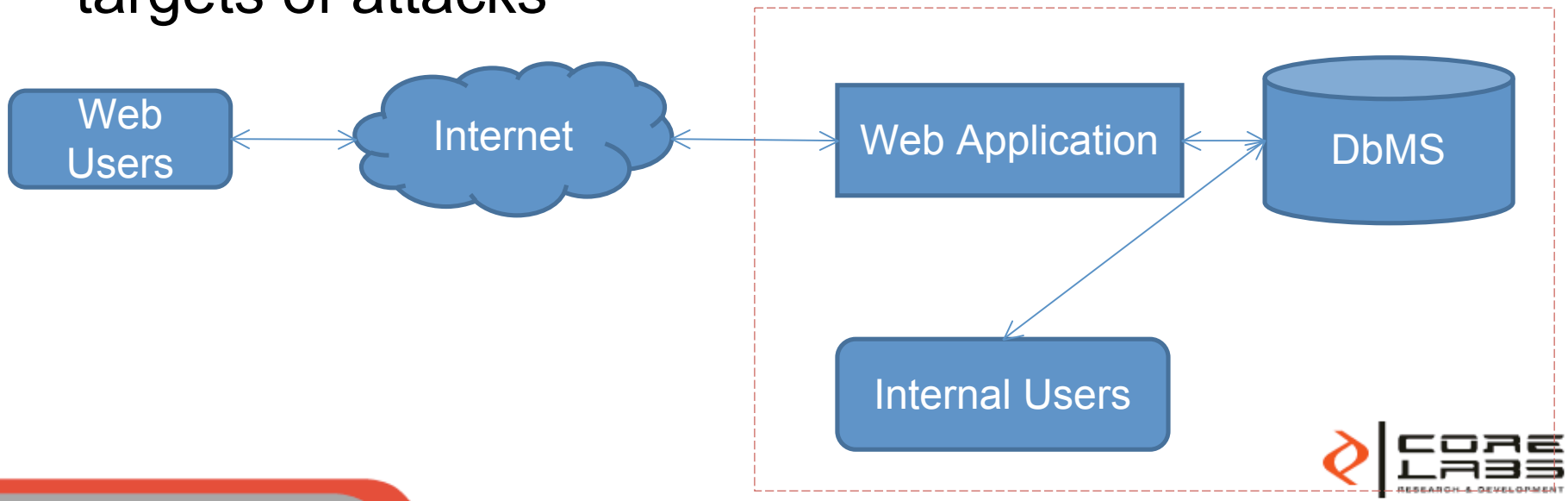
-Core Security Technologies-

Why are DBs interesting to attackers

- Database management systems are used to store huge amounts of data that need to be searched for and refreshed.
  - E.g., target credit card data, health care info., social security numbers and other personal data, ...

- So DbMSs and the servers that host them are targets of attacks



How to compromise a DB

- An attacker breaks into the web server hosting the DB.
  - Insecure configuration, lack of patching, …
- An attacker exploits a SQL-injection vulnerability in the web application (front-end of the DB).
  - Insecure development of the webapp
- An attacker leverages lax permissions and privilege levels in the DB.
  - Someone that can connect to the server, but is not a DB user, compromises an insecure authentication protocol.
  - A legitimate user siphons out confidential data.
- An attacker uses a timing side-channel that relies on the ability to make INSERTs with chosen data.

Main result: scenario

- Consider a populated table in one deployed database management system (e.g., MySQL, MS SQL, Oracle, …)
- Users cannot retrieve data from one column directly, but can insert values in this “privacy-sensitive” column.
- Users can measure the response time of the INSERT transaction.

Intro: Main result (2)

- Then an attacker, passing as a user, can retrieve the values of this column.
  - The success of the attack depends on the accuracy to time inserts and other parameters
  - The “complexity” of the attack can be measured by the number of inserts it requires.
  - The number of inserts required is proportional to the size (in bits) of these values, times the number of values retrieved.

Intro: Main result (3)

- Explicitly,
  - We designed a side-channel attack that relies only on a data structure, B-trees, that is used by most commercial DbMS and the ability to make inserts in the target field and time responses (accurately).
  - We implemented the attack in our lab against a MySQL database and proved it real.

- Further remarks,
  - What does this vulnerability imply?
  - The attack could be improved (complexity).

Indexing table columns, containing sensitive data, is dangerous.

A first example

The CMS

- Imagine a Content Management System (CMS) that:
  - displays a user/password table (as below) and
  - when a user clicks on Password, the table entries are sorted according to the alphabetical order of the passwords.

- A user that is allowed to add entries to the table can then execute a divide et impera search (Latin for binary search) for any other user's password.

Username	Password
Dick	******
Harry	******
Tom	******
….	

The CMS

- Imagine a Content Management System (CMS) that:
  - displays a table of the form and
  - when a user clicks on Password, the table is reordered according to the alphabetical order of the passwords.

- A user that is allowed to register can then execute a divide et impera search for any other user's password.

Username	Password
Dick	******
Harry	******
Tom	******
….	

Username	Password
Tom	******
Dick	******
Harry	******
….	

Hence *Tom's password* < *Dick's password*
There is an information leak!

Abstract and talk outline

1. Database management systems
2. DbMS leak information
3. An attack that exploits this leak
4. Experiments with MySQL
5. Extensions, countermeasures and discussion

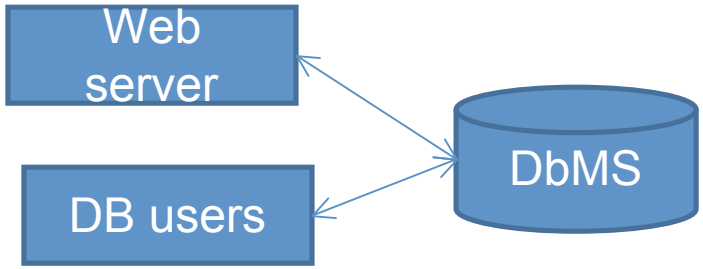
Database management systems

and how is indexing implemented

Intro to DbMSs: Scenario

- Clients connect to access high volumes of data
  - Persistent storage
  - Queries / data manipulation

- Need for efficient searching, writing and deleting data
  - Programming interface.

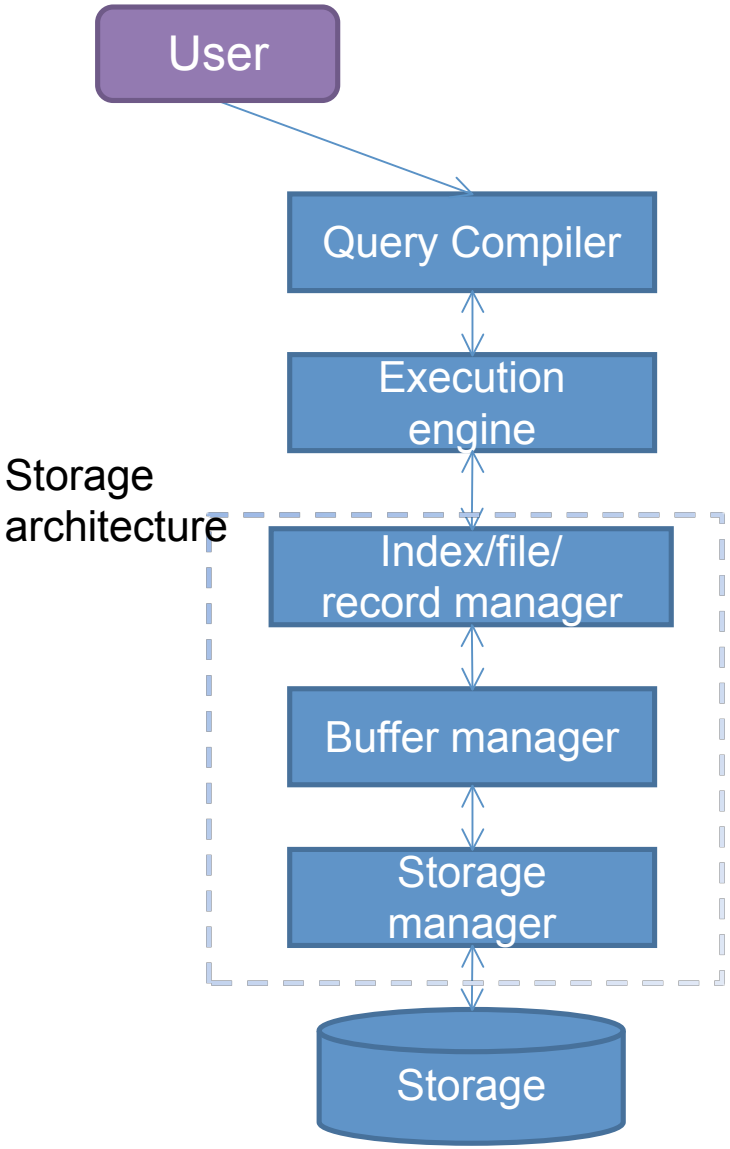


Databases (e.g., RM & SQL)

- The relational model & the SQL standard.
- Data is stored in tables: each row contains a record, and the columns represent the record fields.
- If table rows are not sorted by the values in its fields, then each search/insert/delete query (over a field) requires scanning all the column.
  - Thus, TABLES SHOULD BE SORTED!
  - In fact, updating, inserting and deleting must be optimized.
- Can't store everything in RAM. Must use the hard drive and retrieve data to memory in chunks.

Name	Passport	Football team
Cacho	32102806	San Lorenzo
Pedro	25061305	River
Tomas	9567205	Racing

Database architecture

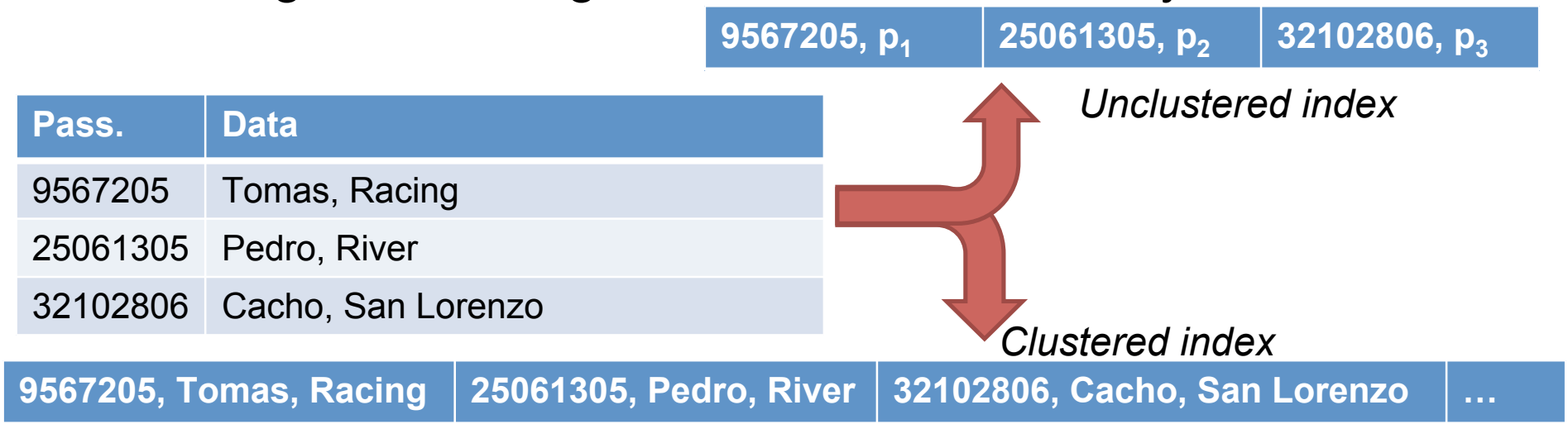


- Data is stored in “sorted chunks” (i.e., pages).
- The querying process:
  - The user makes queries.
  - To answer, the DbMS retrieves only the required pages from *Storage* into memory.
  - The cost of page I/O dominates the cost of typical DB operations.
- To understand more deeply how this *cost* is affected by queries, we must analyze indexes.

Sorting tables

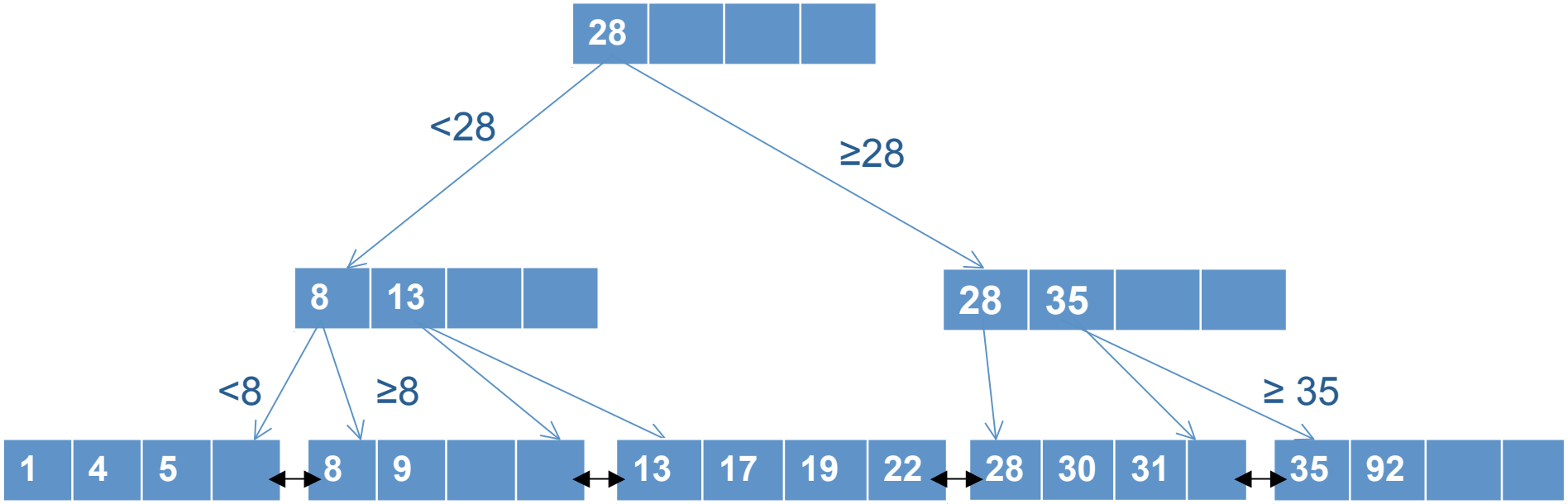
- Each DB table requires one primary index
  - It can be generated automatically by the DbMS, or according to a user-selected search key (e.g., a field).

- Each index produces an (internal) table that is stored by the DbMS in an **index data structure** (e.g., B-trees):
  - Storing each search-key together with a pointer to the data (row), or
  - Storing the data together with the search key.



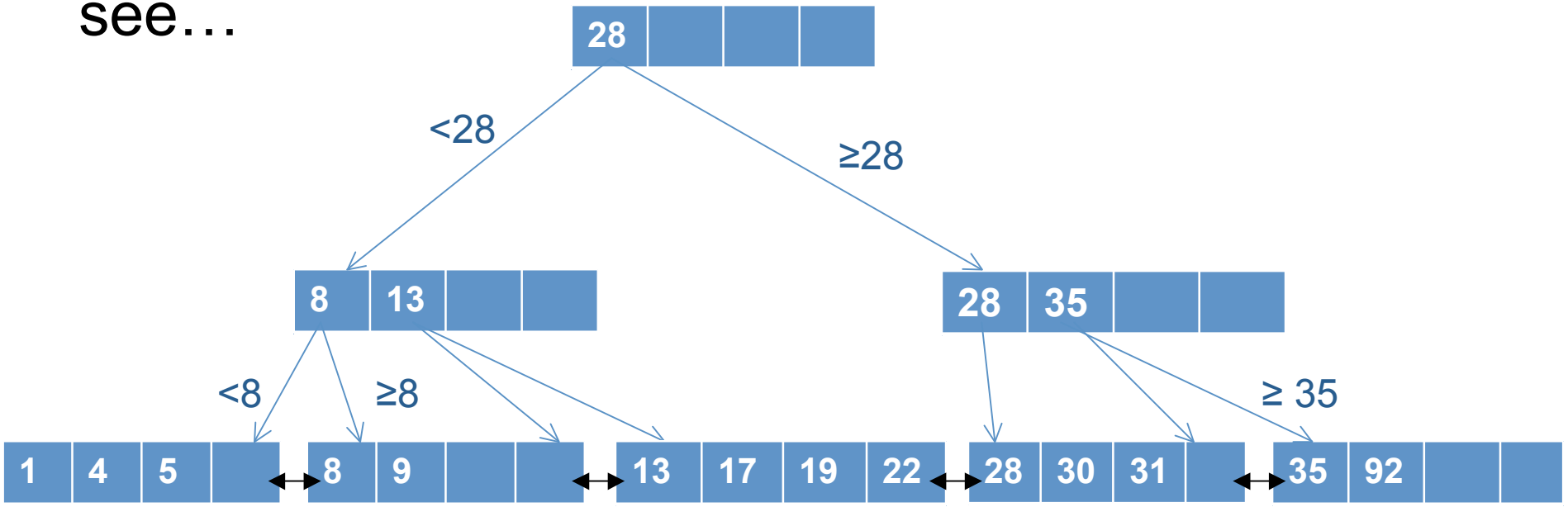
B+ trees design principles

- Each node can store at most a prefixed amount of search keys (and occupies one disk page in Storage).
- Each node must be at least half full.
- Each search key is paired with a pointer or the data.
- Leaf nodes (lower level) are linked in a list (black arrows below).



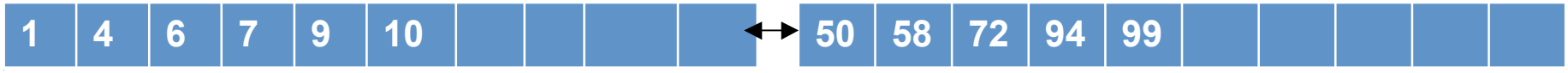
Search & Insert in a B+ tree

- Looking up a search-key value or range is easy, we start from the root node and move down as in the picture below.
- Inserts to non-full nodes are likewise easy.
- Operations that require adding/deleting nodes: let's see…



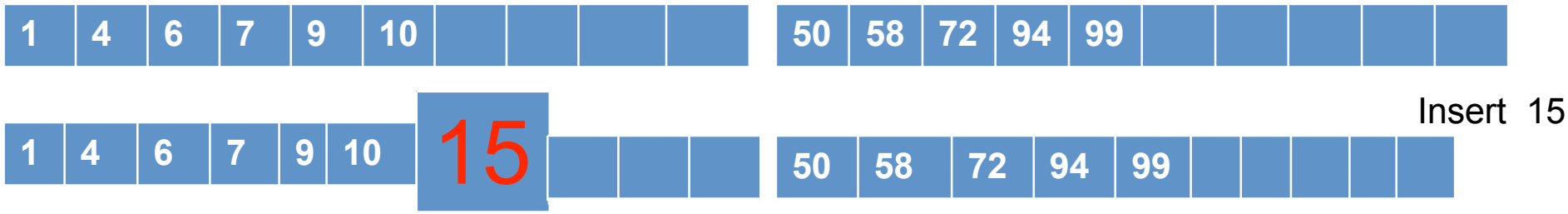
The effect of inserts

(TOY EXAMPLES)

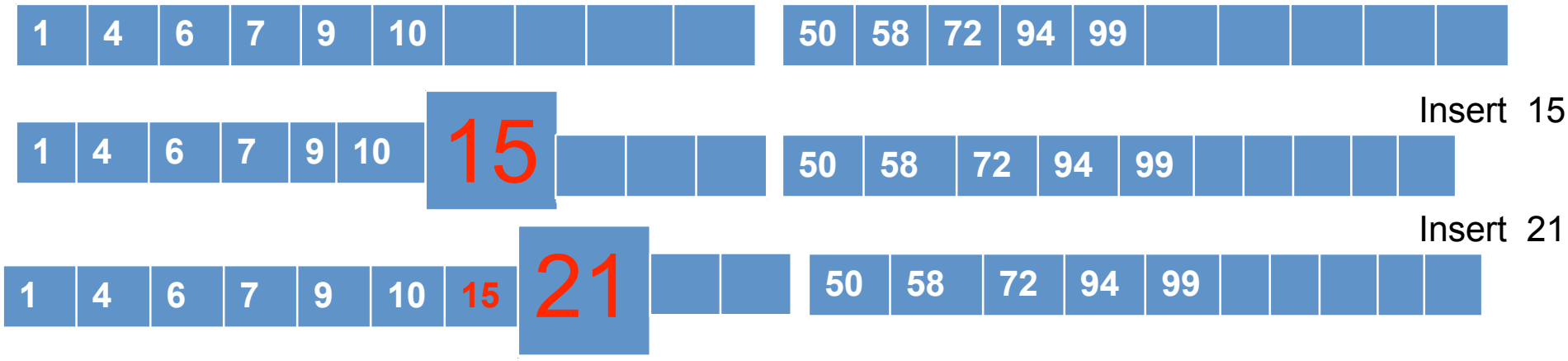


- Let's picture two consecutive leaf nodes.
- We start adding random values until the left leaf is full.

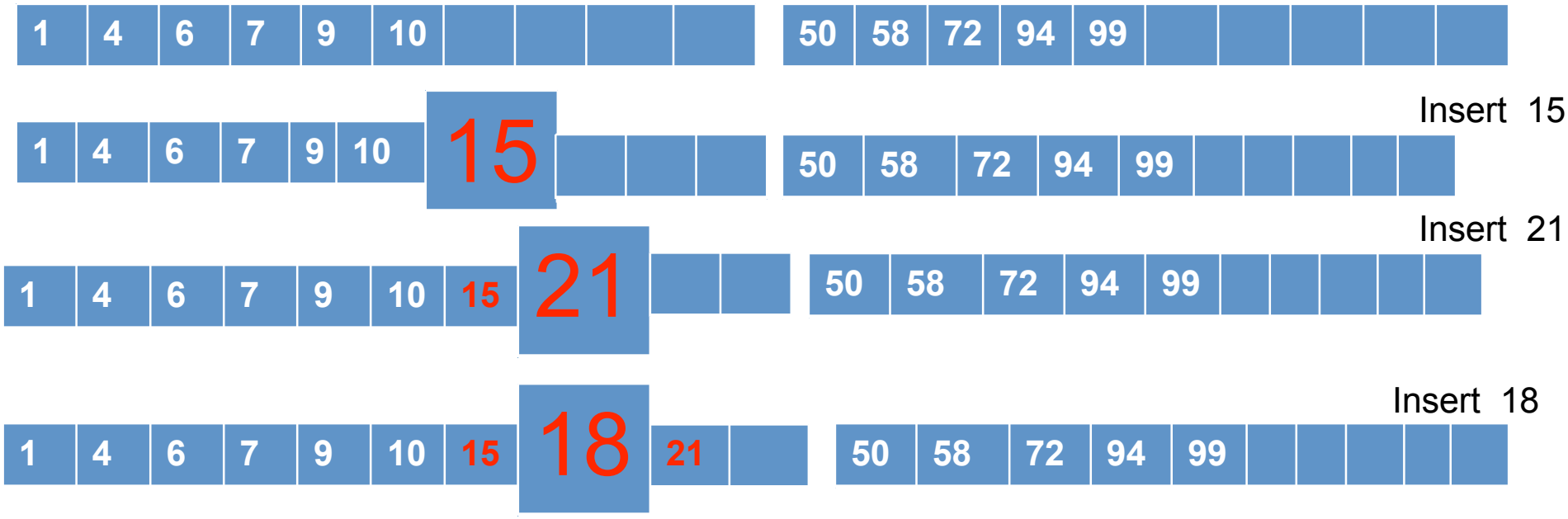
The effect of inserts (2)



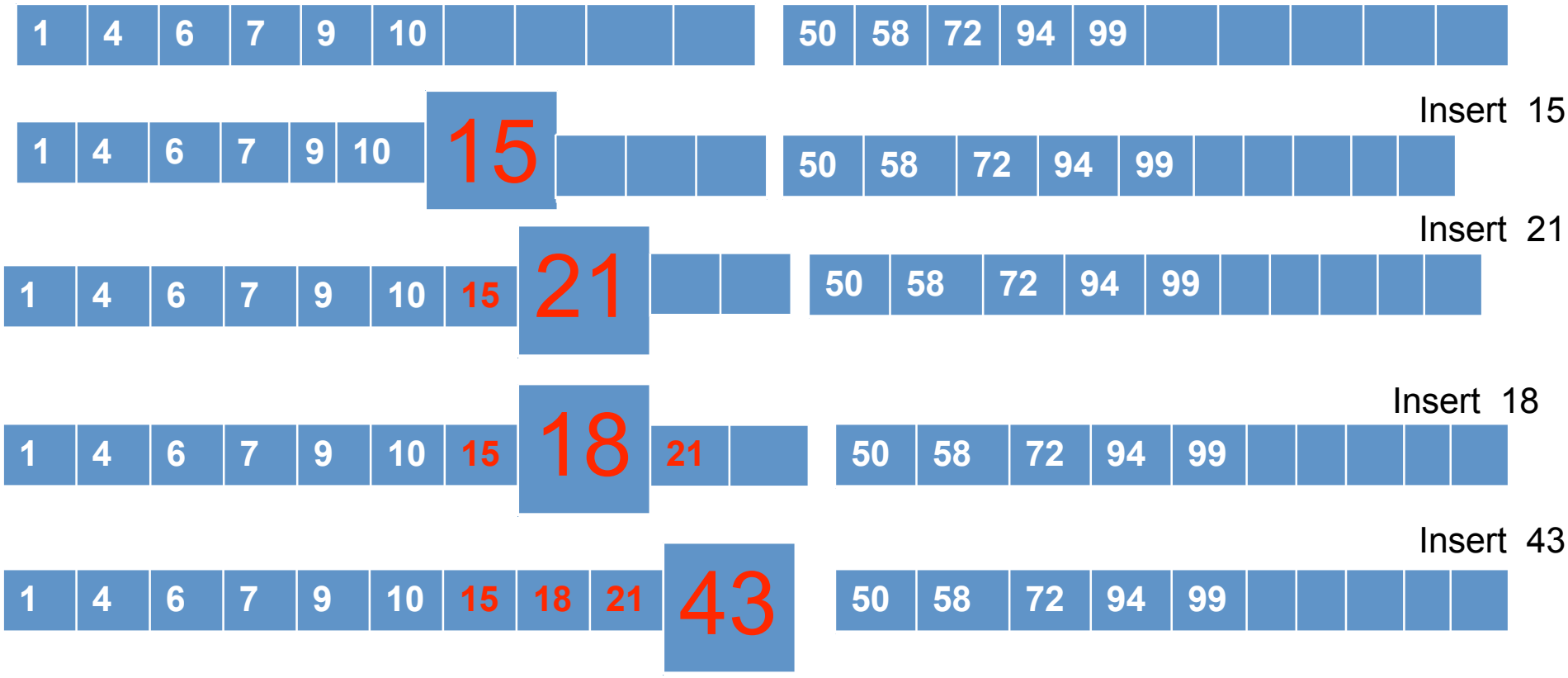
The effect of inserts (2)



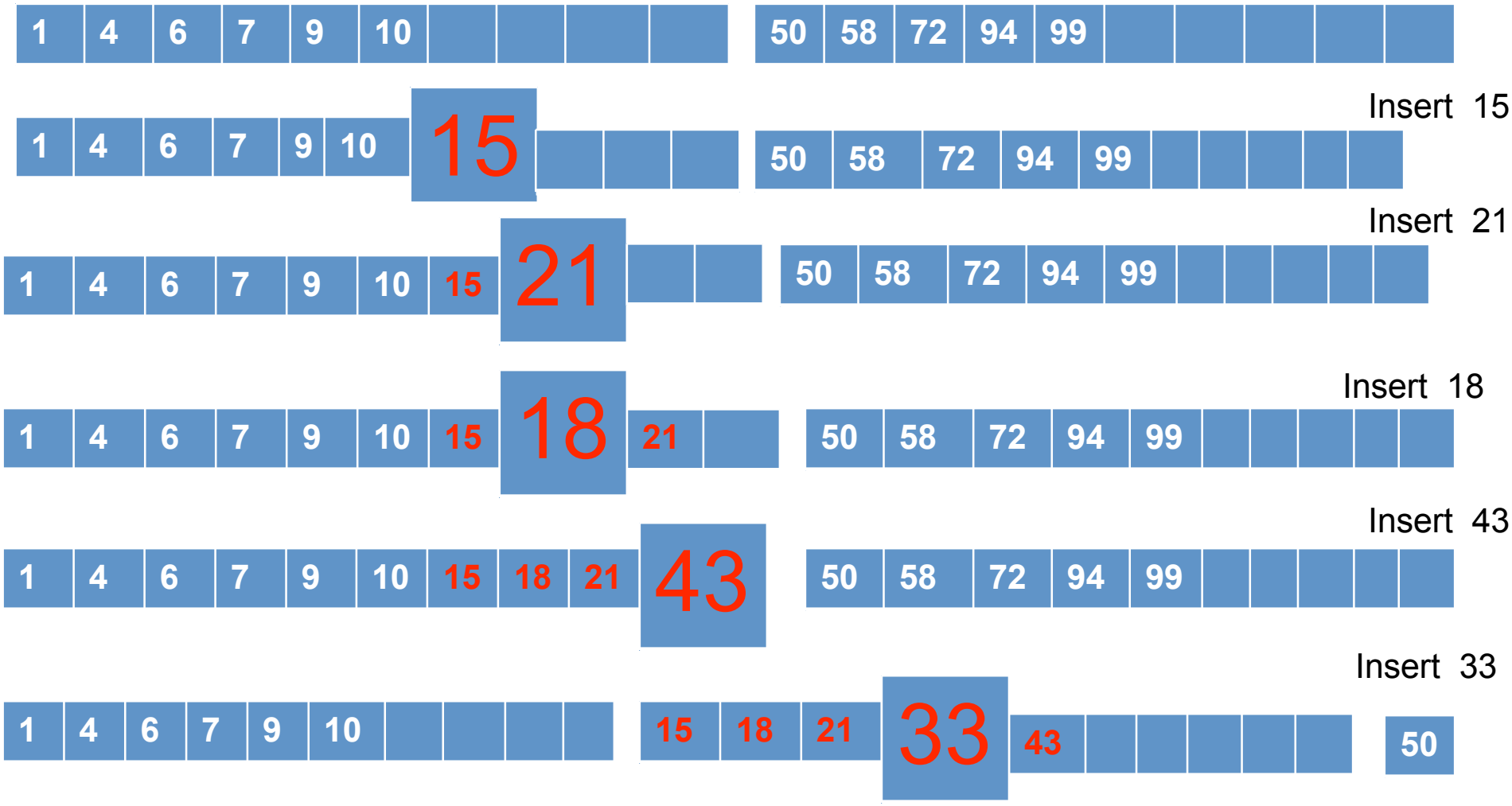
The effect of inserts (2)



The effect of inserts (2)



The effect of inserts (2)



There is a data leak

- Once the left node is full, it is *split* in two.
- Remember: each node must be at least half full.
- An insert that produces a split takes more time than other inserts!

How to turn the information leak into an attack

E.g., can we use split detection to find key values?

Inserting: consecutive values

- Each line represents a leaf, that can fit 10 search keys.
- Previous inserts are in white, the attacker's inserts in red.
- What happens if a user knows the leaf starts at 3, the next leaf starts at 25 and inserts "11,…,16"?

Inserting: consecutive values

- Each line represents a leaf, that can fit 10 search keys.
- Previous inserts are in white, the attacker's inserts in red.
- What happens if a user knows the leaf starts at 3, the next leaf starts at 25 and inserts "11,…,16"?

Inserting: consecutive values (2)

leaf status before inserting 16

- The user inserts11-16 and knows nothing about the pre-existent keys (other than 3).
- Assume that he knows that “16” produced a split!
- Then, he knows that there are 4 keys between 3 and 11!
- If the user has more information about the particular B+-tree implementation, he can guess what is the new leaves configuration.
  - This is because, some DbMSs use an optimization of B+-trees and will not split leaves in halves in certain cases.

Generalizing

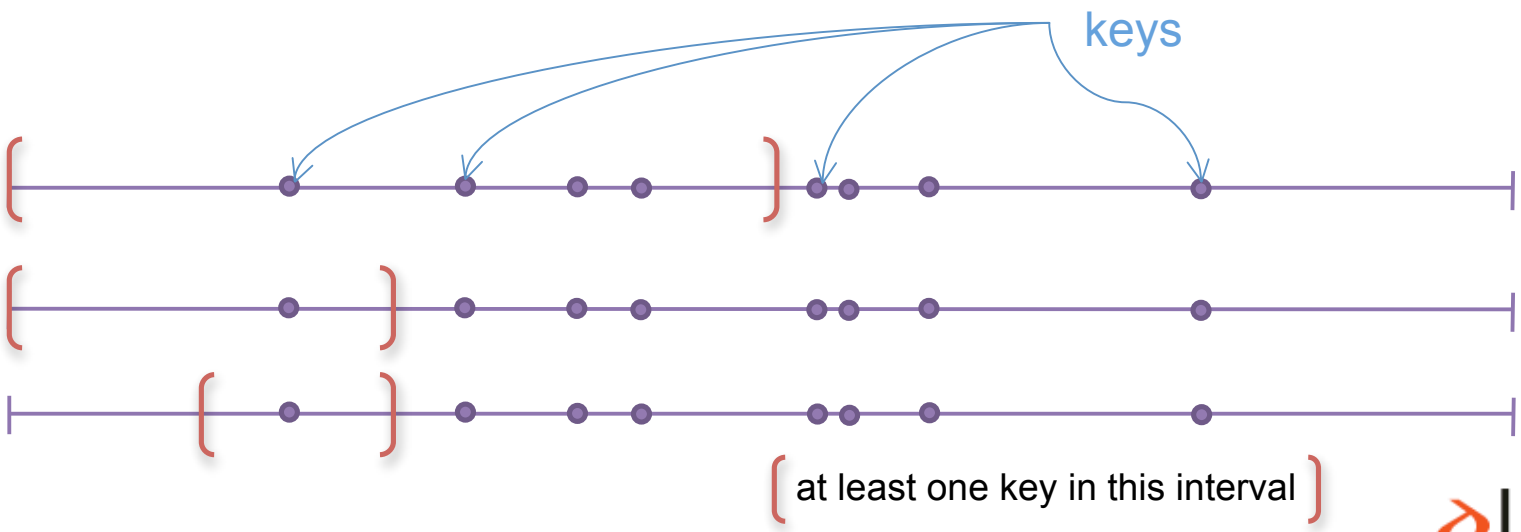
- We have that:
  - If we have the ability to *make inserts on an indexed field* and *detect node splits*,
  - Then, given an two search keys a,b on the same node, we can tell whether there is at least one key between them; plus, learn some info about the new node configuration.

- Why?
  - Assume that *n* keys fit in one node and *n* is known.
  - Insert the keys *b+1, …* until there is a node split.
  - If we stopped before inserting b+n-1, then there must exist keys between a and b!

- Also, since *primary keys* are not allowed to repeat:
  - if we attempt to insert a key with an already existing value we will receive an error –and therefore learn the value of this older key!

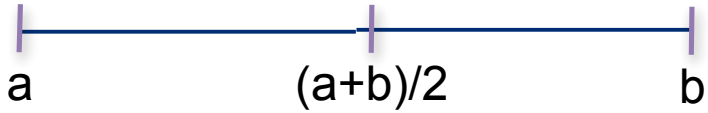
Attack design (1)

- At each step, we divide an interval in two halves, if the first half contains one key, we continue with this.
- When the interval is smaller than the page size, we test all its keys.



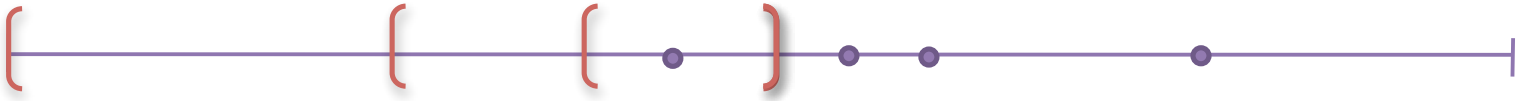
Attack design (2)

- In order to design the attack we need to
  - Develop a split detection algorithm
  - Develop a **binary-search algorithm** that, given an interval [a,b] containing at least a key, determines whether [*a, (a+b)/2*] contains a key (else [*(a+b)/2, b*] contains a key).



Estimating the cost of an attack

- Let's say we are attacking a credit cards database
  - We start with 0 and 10^{17}-1 that includes all the (16 decimal digits, or 56 binary digits) credit cards.
  - Assume that each page disk contains $n=512=2^9$ keys.



- We need to invoke ≈46=(56-10) times the binary-search algorithm, each invocation requiring <512 inserts, plus the search in the last step. This amounts to an upper bound of 11500 inserts.

Attacking MySQL-InnoDB

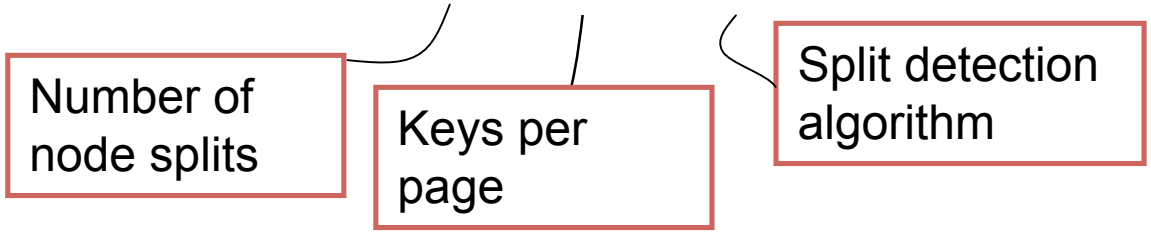
1. Scenario and Results
2. Attack details
   a) How splitting works in InnoDB
   b) The attack algorithm
   c) Node Split detection algorithm
3. Statistics

Scenario summary

- MySQL is an open-source and very popular DbMS.
- InnoDB is one of the storage engines that come with MySQL
  - It requires a clustered index and uses a B+-tree structure for indexes.
- The DbMS
  - Clean install of MySQL-InnoDB
  - Populate the database with different data types and table sizes
  - Connect as a MySQL user through an Intranet (i.e., one switch)
  - Only allowed to make inserts.
- Noise
  - There are other users in the net
  - No other users connecting to MySQL.
  - The web server might run other services.

Experimental results

- We tested our attack
  - against three tables, with one key 113111 plus other uniformly chosen values between 0 and 10M.
  - The (theoretic) estimate for the number of inserts required for the attack is 6 x 574 x 3 = 14100.



# of keys	Success rate	# of inserts	Time
1	3/3	14100	10:37
101	3/3	13145	10:39
1001	3/5	14371	10:47

Attack details

Page splitting in InnoDB

- We need to understand page splits under InnoDB,
  - Indexes are stored in a B+-tree structure, with some *ad hoc* optimizations.
  - The restructuring of the tree after a node addition depends on the last few inserts.
  - When making consecutive inserts it has a special behavior.
  - Else, pages are split in halves when full.

Attack details

InnoDB and B+-trees

- We analyze for a non-full node

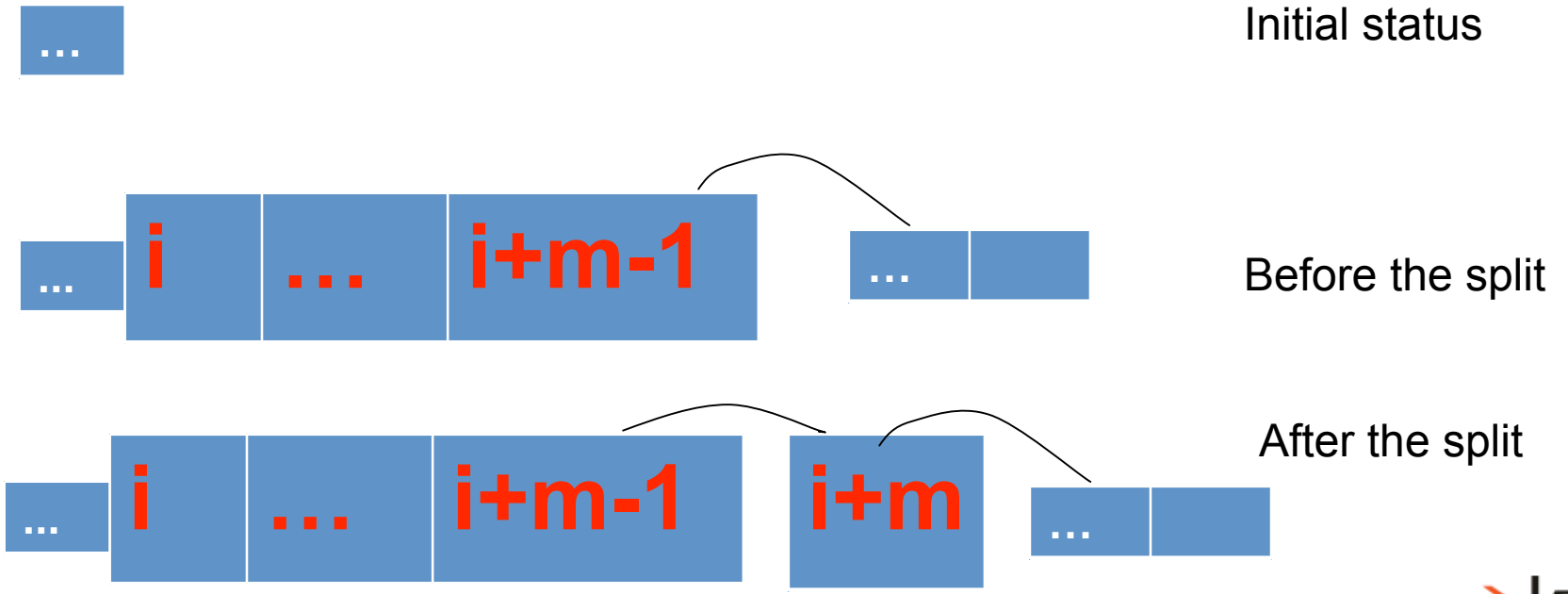
what is the effect of inserting consecutive values i,i+1,… until there is a split?

- When i has *no value* to its right.
- When i has *one* key to its right.
- When i has *several* keys to its right.

Attack details

Case 1

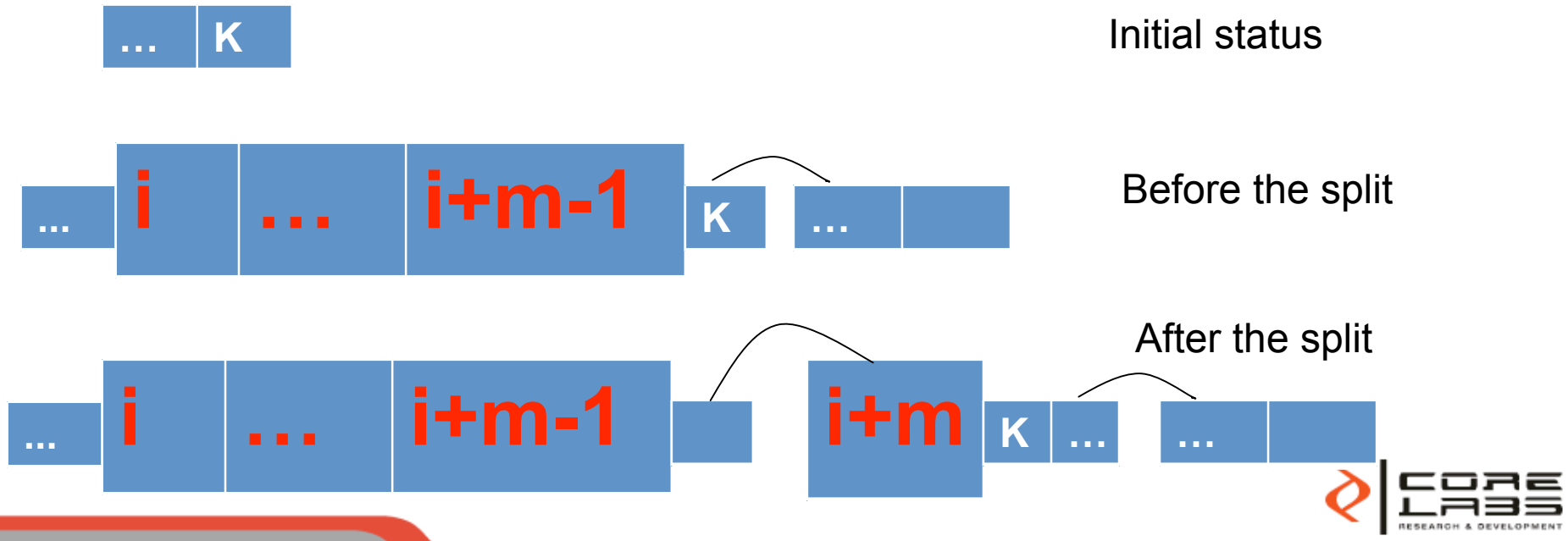
- What is the effect of inserting consecutive values i,i+1,… until there is a split?
  - When i has *no value* to its right.



Attack details

Case 2

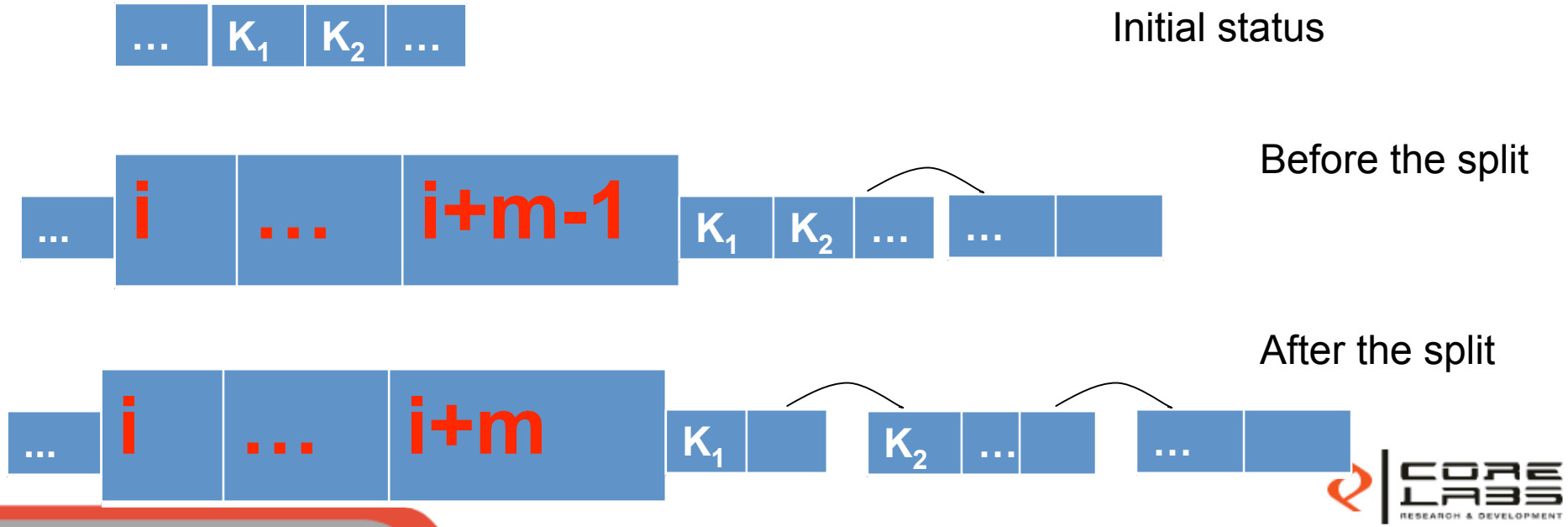
- What is the effect of inserting consecutive values i,i+1,… until there is a split?
  - When i has *one key* to its right.



Attack details

Case 3

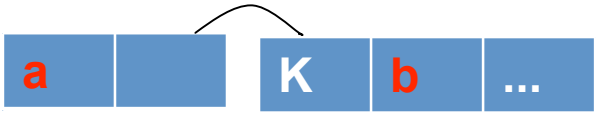
- What is the effect of inserting consecutive values i,i+1,… until there is a split?
  - When i has several keys to its right.



Attack details

How to retrieve a secret key K

1. SETUP
   - We insert certain values so that: we get values *a* and *b* such that a< K <b, there is no other key between *a* and *b,* and K is the first element in its page.

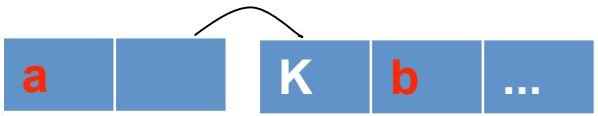


2. BINARY SEARCH
   - We iterate over a procedure that, at each step, it halves the interval, it can tell in which half is *K*, and K is still the first element in its page.
3. FINAL STEP:
   - When the size of the interval is smaller than the page size, we check a, a+1, a+2,… until we find K.

Attack details

The binary search algorithm

- As input we have values a, b such that
  - a < K < b, where a and b are known and K is unknown.
  - There is no value other than K between a and b.
  - K is the first element on its page

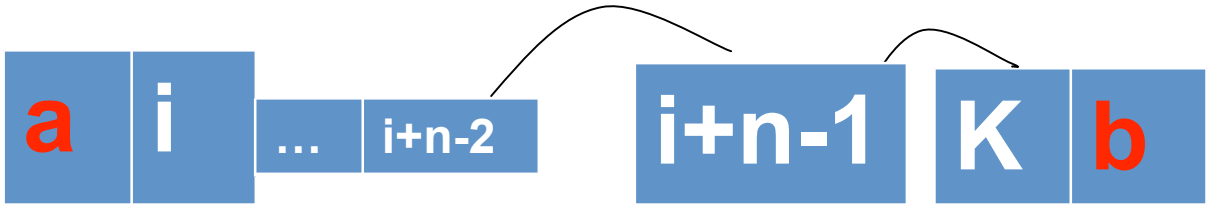


- What is the effect of inserting (a+b)/2, (a+b)/2+1,… until there is a split?

IF (a+b)/2<K THEN

The binary search algorithm

- If all the values inserted are smaller than K the state of the tree after the split would be



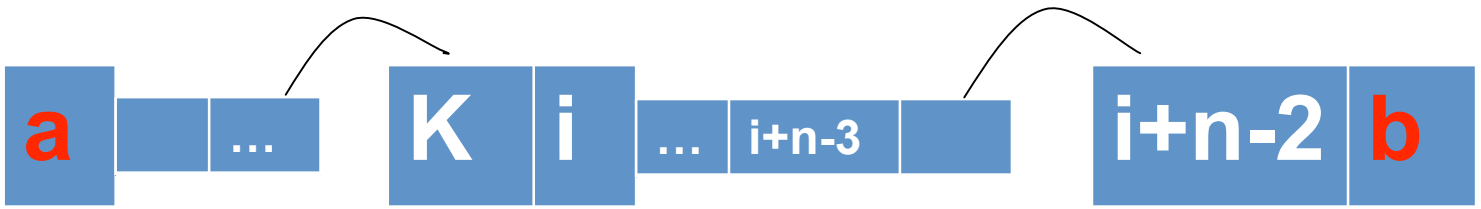
(here i = (a+b)/2.)

Notice that the number of values we inserted is n = the size of a page!

IF (a+b)/2>K THEN

The binary search algorithm

- If all the values inserted are greater than K the state of the tree after the split would be



Notice that the number of values we inserted is n-1

This assumes that the leaf on the right contained no other values than K,b. Else the split occurs before the (n-1)-th insert.

Attack details

The binary search algorithm

- By looking at the number of values we insert until there is a split, we know if (a+b)/2 < K or (a+b)/2 > K, so we can shorten the original interval [a,b] in half as follows

  if we inserted n values, we set

  a := (a+b)/2 + n

  if we inserted n-1 values

  b := (a+b)/2 – 1

- So repeating this procedure we get that the search of K is done at an exponential speed!

Split detection

Split detection

- About noise:
  - In most cases the inserts that do not produce splits take much less time than inserts that produce splits.
  - But, there are many indistinguishable cases.
  - In any case, there is a “time threshold value.”
  - Timing with functions `QueryPerformanceCounter` and `QueryPerformanceFrequency` in kernel32.dll
- An experiment
  - we insert consecutive values and time them t[1], t[2],…
  - For each i, such that the values t[i], t[i+n], t[i+2n] are all bigger than the time threshold, we check whether they correspond to node splits (Case 1).
  - Yes, it is improbable that t[i], t[i+n], t[i+2n]>threshold and no split occurred.

Split detection (2)

- The previous experiment can be translated into a split detection algorithm.
  - We need a table (e.g., (i,i+n,i+2n) => Case 1, (i,i+n-1,i+2n-1)=> Case 2, etcetera).

- INPUT: a value i.
- OUTPUT: left node or right node.

- Remarks:
  - the algorithm is probabilistic.
  - it may need to make more than 2n inserts.
  - This is basic signal processing, and could be improved!

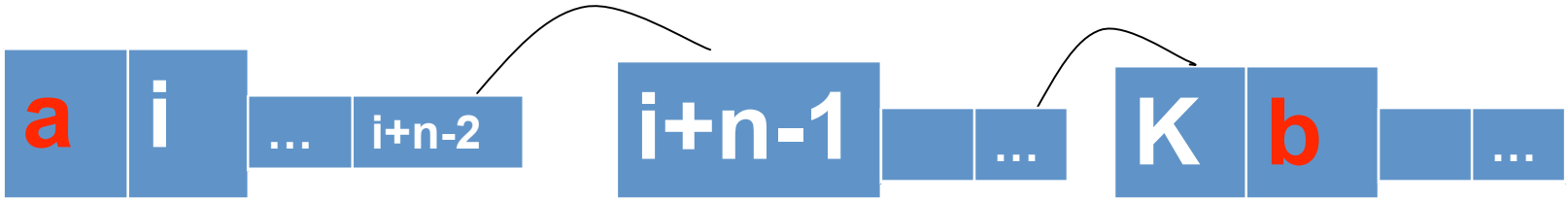
Combining both algorithms

- We need to piece together the split detection and binary search algorithms, and show that this produces the expected result.

- Let's return to the cases (a+b)/2 < K and K<(a+b)/2

Combining both algorithms

- First, when (a+b)/2 < K



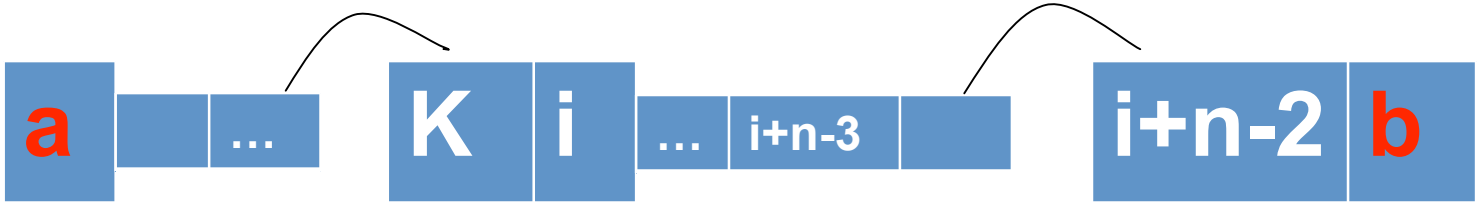
In this case, if we insert i, i+1 … and eventually stop when we detect a split, e.g., at (i+n-1,i+2n-1,i+3n-1), then notice that:

- Node splits correspond to cases 1,1 and 1.
- i+3n-1 < K < b, and there is no key between i+3n-1 and b.
- K remains the first element in a node.

So we take a:=i+3n-1 and continue with the binary search.

Combining both algorithms

- Second, when K<(a+b)/2



In this case, if we insert i, i+1 … and eventually stop when we detect a split, e.g., at (i+n-2,i+2n-3,i+3n-4), then notice that:

- Node splits correspond to cases 1, 2 and 2.
- a < K < i, and there is no key between i+2(n-1)-1 and b.
- K remains the first element in a node

So we take b:=i and continue with the binary search.

Combining both algorithms

- Similarly, the setup procedure can be combined with this split detection algorithm.

- The number of inserts required to execute the attack is multiplied by 3 (we expect!).
  - This is nothing if we consider that the speed of the search is logarithmic (e.g., $3 \cdot \log(N) << N$)

Future work and coutermeasures

Future work

- How to improve our attack
  - Can we get outside the lab?
  - Better split detection through signal processing.
  - Require less inserts in order to produce one split.
  - Heuristic optimizations: E.g., if the values are assumed to be uniformly distributed, then we can replace the binary search for a more general divide-and-conquer.
  - Optimize the attack for getting many keys.

Future work (2)

- Other DbMSs require a lot of work!
  - Varies depending on DbMS implementation details.
  - Transactional systems, caches and journaling can play for/against the attack.
  - To adapt our technique, say to other DbMSs which use B-tree indexing, one needs to:
    - Provide split detection algorithms
    - Find a method to use the node split information leak to narrow the space for potential keys.

Countermeasures

- Don’t index privacy searching data: then every query lasts the same amount of time!
- Transaction throttling: Block a user from making more than 10 inserts per day/session.
- Blinding at the DbMS: encode the search-key values.
- Introduce random time delays so that the two types of inserts are indistinguishable from the time they take.
- NIDS: Block certain types of behavior.

Thanks!

Any questions?