Data Storage, Indexing Structures for Files

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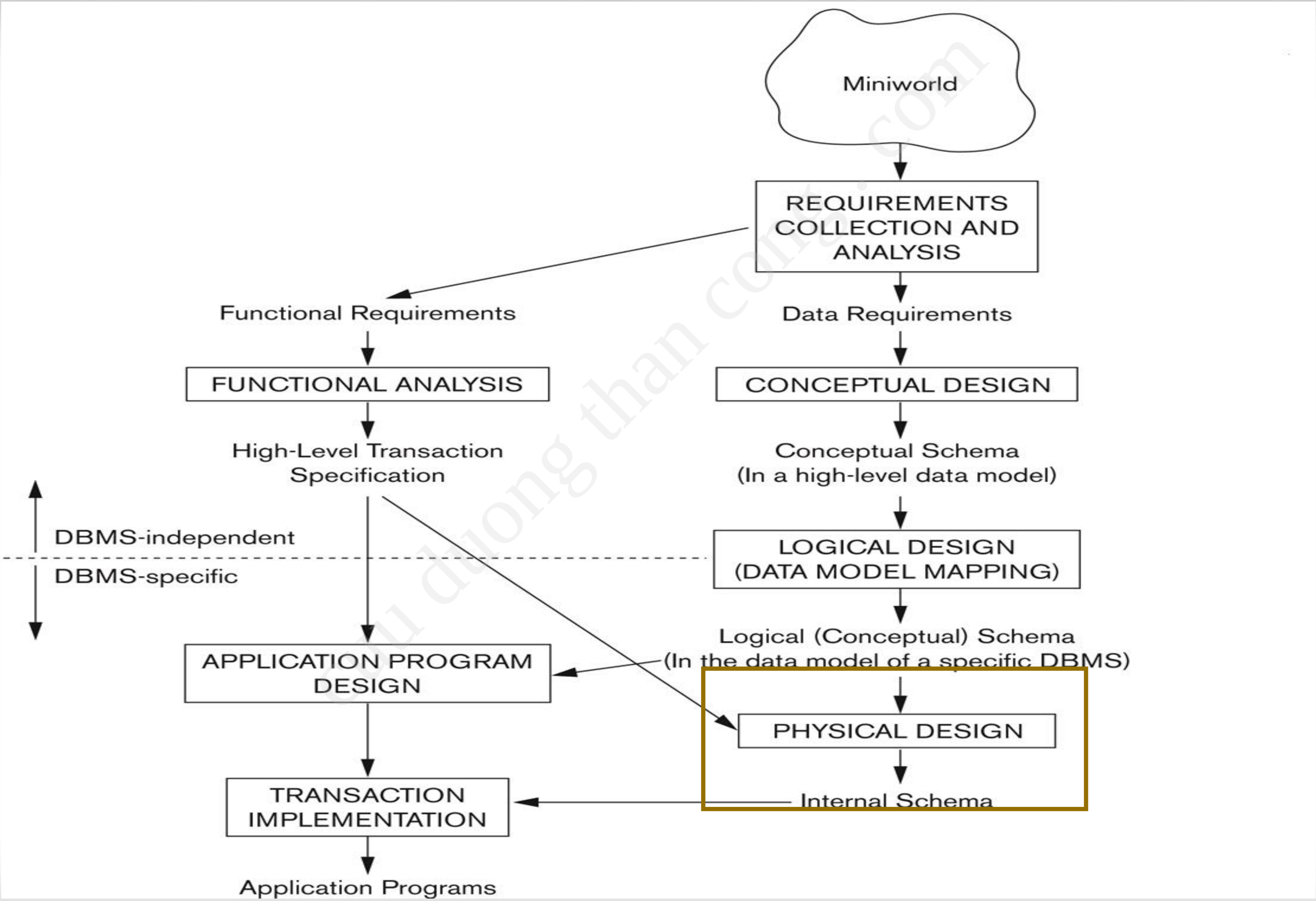
Overview of Database Design Process



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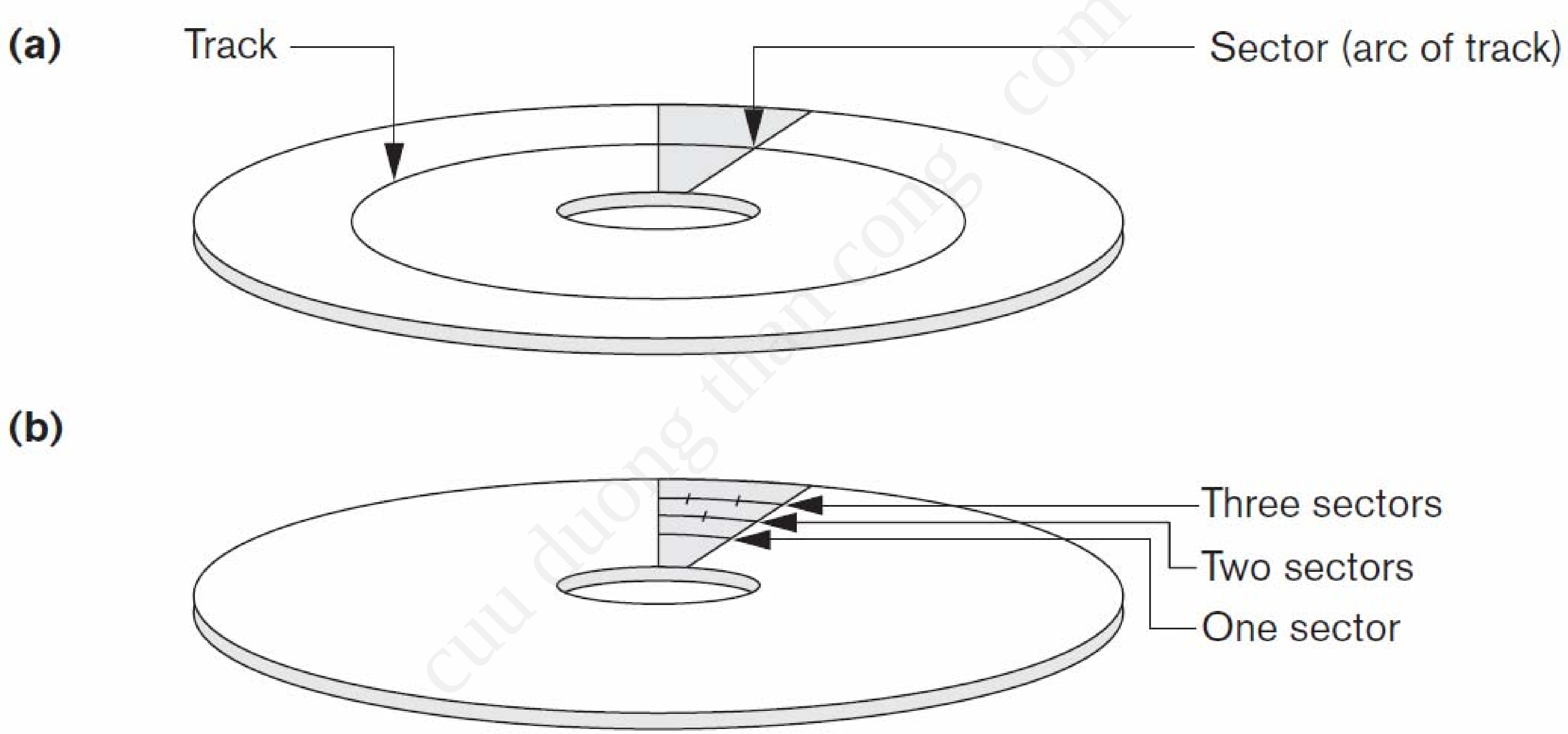
Disk Storage Devices

- Preferred secondary storage device for high storage capacity and low cost.
- Data stored as magnetized areas on magnetic disk surfaces
- A *disk pack* contains several magnetic disks connected to a rotating spindle.
- Disks are divided into concentric circular *tracks* on each disk *surface* .
  - Track capacities vary typically from 4 to 50 Kbytes.

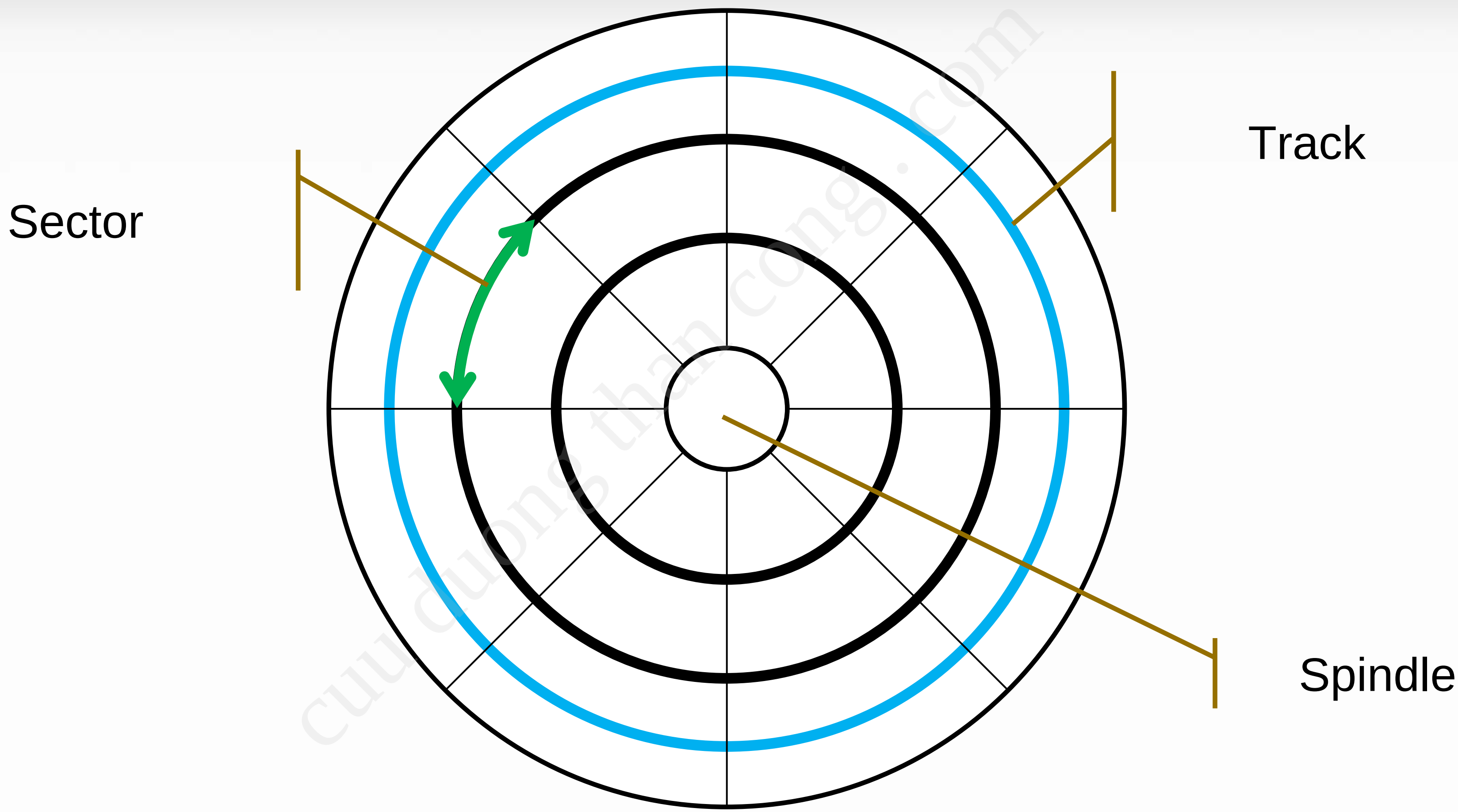
Disk Storage Devices (cont.)



Disk Storage Devices (cont.)

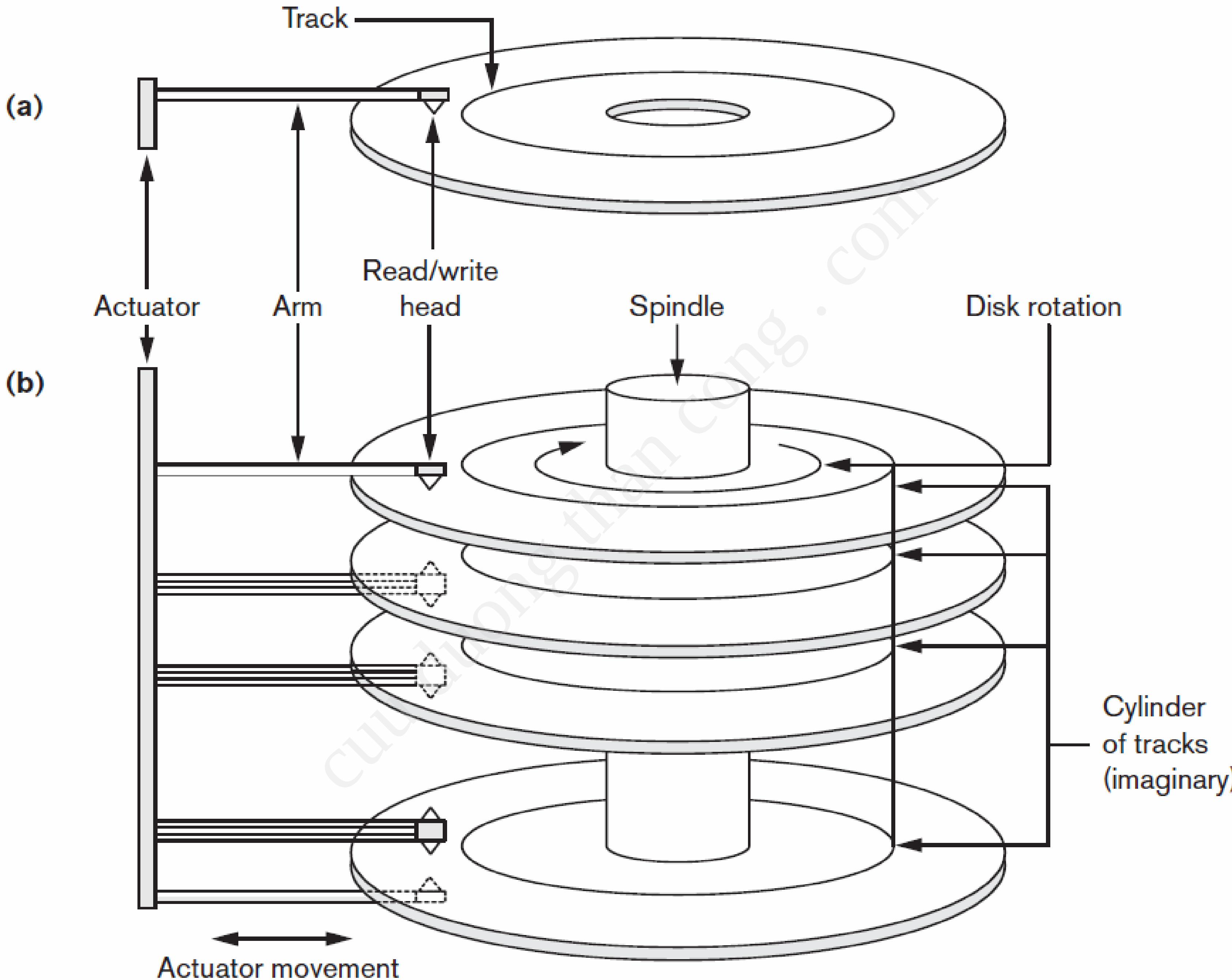
- A track is divided into **blocks** or **sectors**
  - The block size B is fixed for each system.
    - Typical block sizes range from B=512 bytes to B=4096 bytes.
  - Whole block data is transferred between disk and main memory for processing.

Disk Storage Devices (cont.)



Disk Storage Devices (cont.)

- A **read-write head** moves to the track that contains the block to be transferred.
  - Disk rotation moves the block under the read-write head for reading or writing.
- A physical disk block (hardware) address consists of:
  - a cylinder number (imaginary collection of tracks of same radius from all recorded surfaces)
  - the track number or surface number (within the cylinder)
  - and block number (within track).
- Reading or writing a disk block is time consuming because of the seek time s and rotational delay (latency) **rd**.
- *Double buffering* can be used to speed up the transfer of contiguous disk blocks.



Track
(a)
(b)
Actuator
Arm
Read/write
head
Spindle
Disk rotation
Cylinder
of tracks
(imaginary)
Actuator movement

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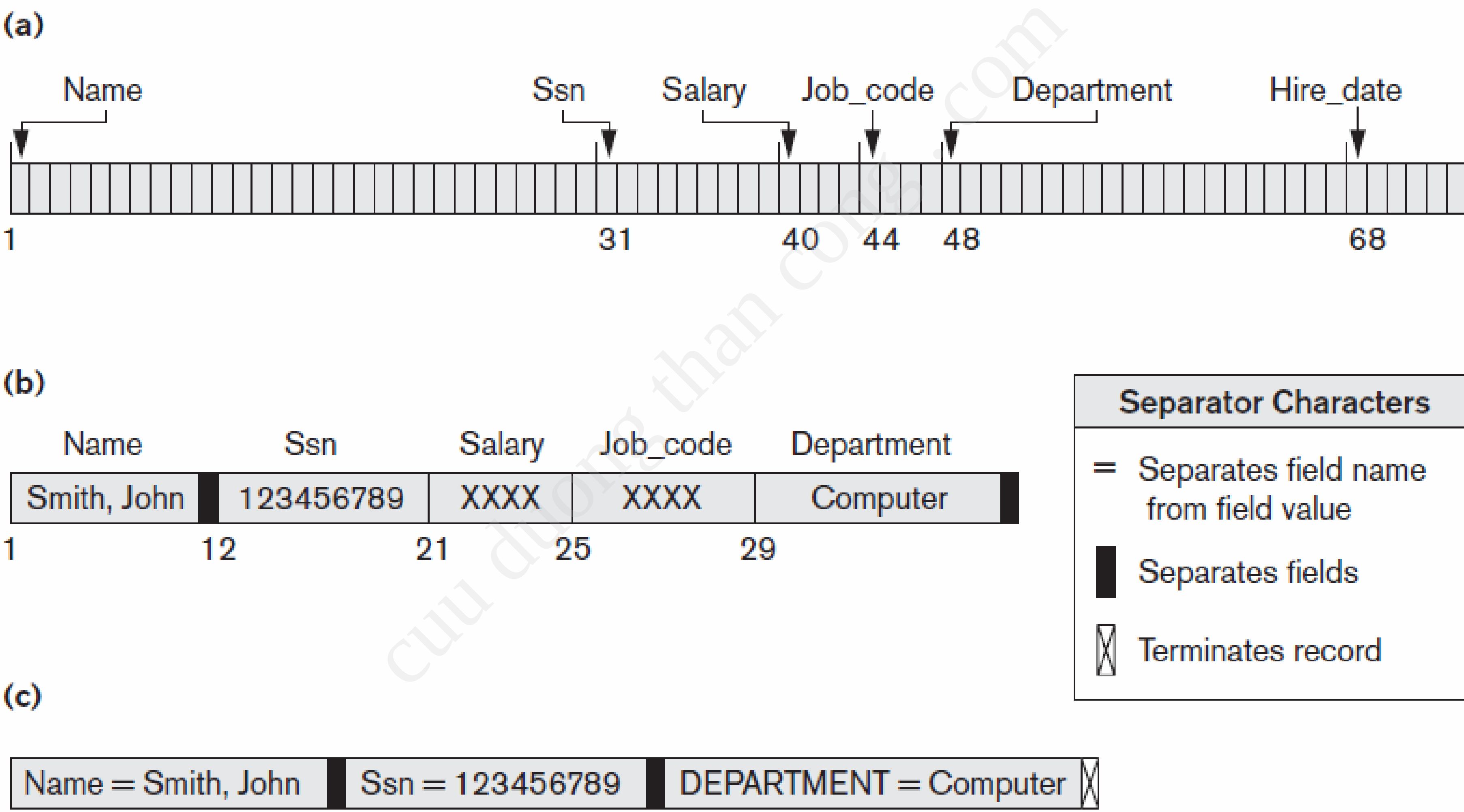
Records

- Fixed and variable length records.
- Records contain fields which have values of a particular type.
  - E.g., amount, date, time, age.
- Fields themselves may be fixed length or variable length.
- Variable length fields can be mixed into one record:
  - Separator characters or length fields are needed so that the record can be "parsed".

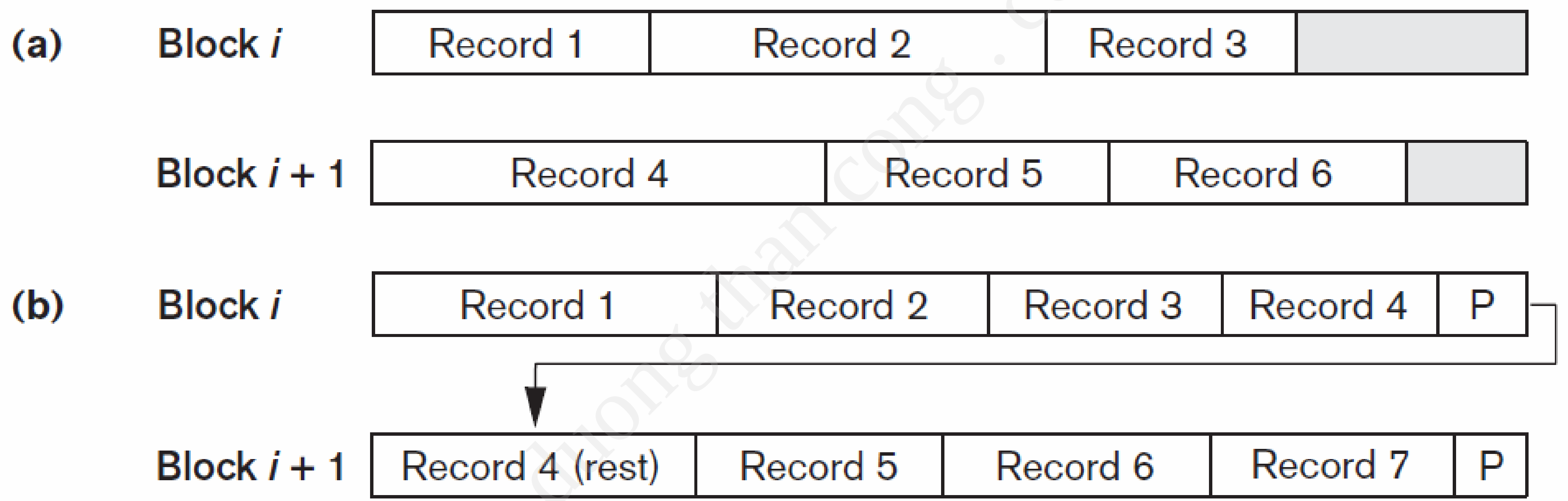
Records (cont.)



Blocking

- **Blocking:** refers to the storage of a number of records in one block on the disk.
- **Blocking factor (*bfr*):** refers to the number of records per block.
- There may be empty space in a block if an integral number of records do not fit in one block.
- **Spanned Records:** refer to records that exceed the size of one or more blocks and hence span a number of blocks.

Blocking (cont.)



Files

- A **file** is a *sequence* of records, where each record is a collection of data values (or data items).
- A **file descriptor** (or **file header**) includes information that describes the file, such as the *field names* and their *data types*, and the addresses of the file blocks on disk.
- The **blocking factor bfr** for a file is the (average) number of file records stored in a disk block.
- A file can have **fixed-length** records or **variable-length** records.

Files (cont.)

- File records can be **unspanned** or **spanned**:
  - **Unspanned**: no record can span two blocks
  - **Spanned**: a record can be stored in more than one block
- The physical disk blocks that are allocated to hold the records of a file can be *contiguous, linked, or indexed*.
- In a file of fixed-length records, all records have the same format. Usually, unspanned blocking is used with such files.
- Files of variable-length records require additional information to be stored in each record, such as **separator characters** and **field types**.
  - Usually spanned blocking is used with such files.

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Operation on Files

Typical file operations include:

- **OPEN:** Reads the file for access, and associates a pointer that will refer to a *current* file record at each point in time.
- **FIND:** Searches for the first file record that satisfies a certain condition, and makes it the current file record.
- **FINDNEXT:** Searches for the next file record (from the current record) that satisfies a certain condition, and makes it the current file record.
- **READ:** Reads the current file record into a program variable.
- **INSERT:** Inserts a new record into the file, and makes it the current file record.

Operation on Files (cont.)

- **DELETE:** Removes the current file record from the file, usually by marking the record to indicate that it is no longer valid.
- **MODIFY:** Changes the values of some fields of the current file record.
- **CLOSE:** Terminates access to the file.
- **REORGANIZE:** Reorganizes the file records. For example, the records marked deleted are physically removed from the file or a new organization of the file records is created.
- **READ_ORDERED:** Read the file blocks in order of a specific field of the file.

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Unordered Files

- Also called a **heap** or a **pile** file.
- New records are inserted at the end of the file.
- A **linear search** through the file records is necessary to search for a record.
  - This requires reading and searching half the file blocks on the average, and is hence quite expensive.
- Record insertion is quite efficient.
- Reading the records in order of a particular field requires sorting the file records.

Ordered Files

- Also called a **sequential** file.
- File records are kept sorted by the values of an *ordering field*.
- Insertion is expensive: records must be inserted in the correct order.
  - It is common to keep a separate unordered *overflow* (or *transaction*) file for new records to improve insertion efficiency; this is periodically merged with the main ordered file.
- A **binary search** can be used to search for a record on its *ordering field* value.
  - This requires reading and searching $\log_2$ of the file blocks on the average, an improvement over linear search.
- Reading the records in order of the ordering field is quite efficient.

	NAME	SSN	BIRTHDATE	JOB	SALARY	SEX
block 1	Aaron, Ed					
	Abbott, Diane					
	⋮					
	Acosta, Marc					
block 2	Adams, John					
	Adams, Robin					
	⋮					
	Akers, Jan					
block 3	Alexander, Ed					
	Alfred, Bob					
	⋮					
	Allen, Sam					
⋮						
block n –1	Wong, James					
	Wood, Donald					
	⋮					
	Woods, Manny					
block n	Wright, Pam					
	Wyatt, Charles					
	⋮					
	Zimmer, Byron					

Average Access Times

- The following table shows the average access time to access a specific record for a given type of file:

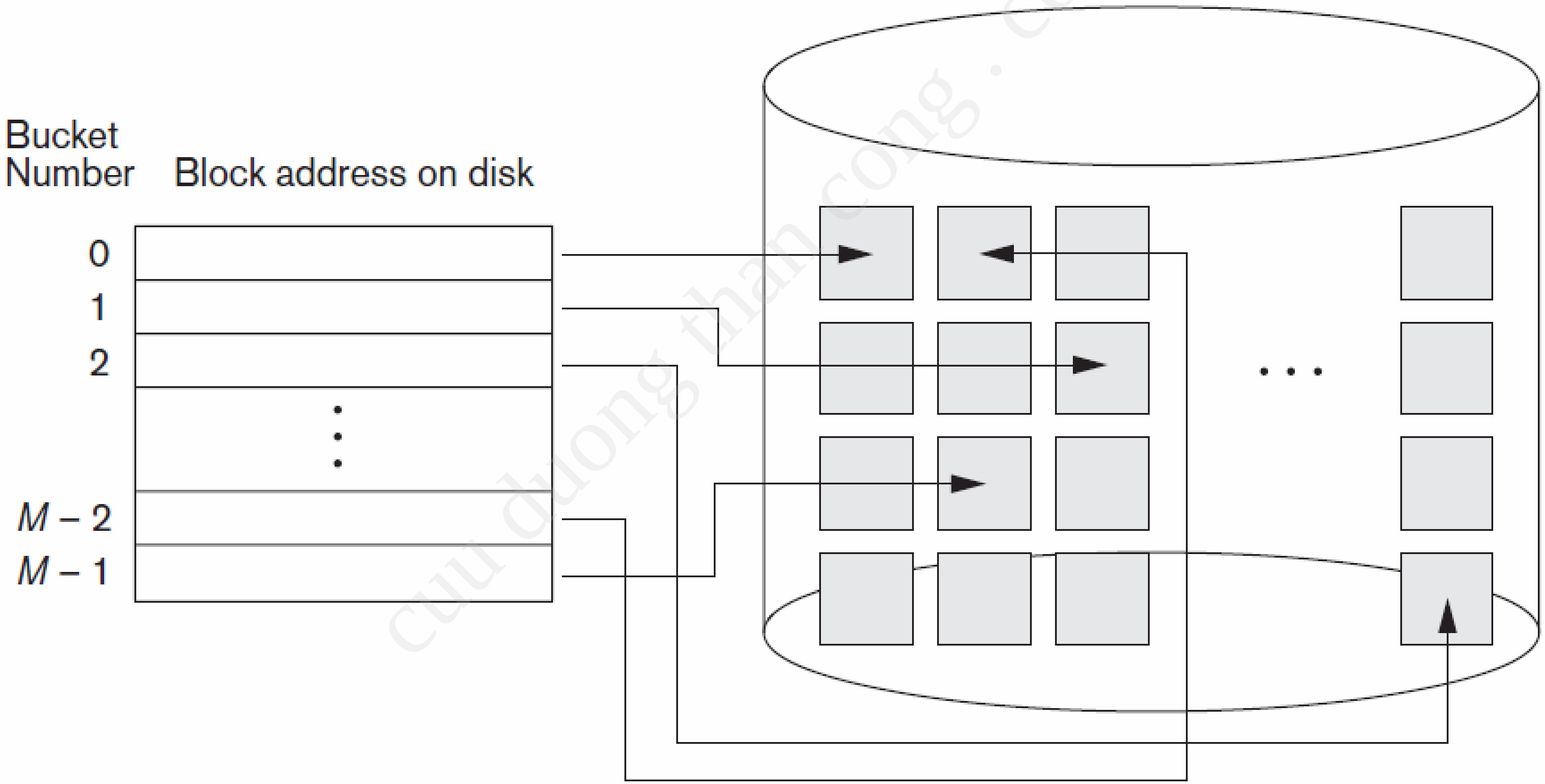
Table 17.2 Average Access Times for a File of *b* Blocks under Basic File Organizations

Type of Organization	Access/Search Method	Average Blocks to Access a Specific Record
Heap (unordered)	Sequential scan (linear search)	$b/2$
Ordered	Sequential scan	$b/2$
Ordered	Binary search	$\log_2 b$

Hashed Files

- Hashing for disk files is called **External Hashing.**
- The file blocks are divided into M equal-sized **buckets**, numbered $bucket_0$, $bucket_1$, ..., $bucket_{M-1}$.
  - Typically, a bucket corresponds to one (or a fixed number of) disk block.
- One of the file fields is designated to be the **hash key** of the file.
- The record with hash key value K is stored in bucket i, where i=h(K), and h is the **hashing function**.
- Search is very efficient on the hash key.
- Collisions occur when a new record hashes to a bucket that is already full.
  - An overflow file is kept for storing such records.
  - Overflow records that hash to each bucket can be linked together

Hashed Files (cont.)



Hashed Files (cont.)

- There are numerous methods for collision resolution, including the following:
  - ***Open addressing:*** Proceeding from the occupied position specified by the hash address, the program **checks the subsequent positions in order until an unused** (empty) position is found.

- h(K) = K mod 7

0	1	2	3	4	5	6
	1		3	11		6

- Insert 8

	1	8	3	11		6

- Insert 15

	1	8	3	11	15	6

- Insert 13

13	1	8	3	11	15	6

Hashed Files (cont.)

- There are numerous methods for collision resolution, including the following:
  - ***Chaining:***
    - Various overflow locations are kept: extending the array with a number of overflow positions.
    - A pointer field is added to each record location.
    - A collision is resolved by placing the new record in an unused overflow location and setting the pointer of the occupied hash address location to the address of that overflow location.
  - ***Multiple hashing:***
    - The program applies a second hash function if the first results in a collision.
    - If another collision results, the program uses open addressing or applies a third hash function and then uses open addressing if necessary.

Hashed Files (cont.) - Overflow handling

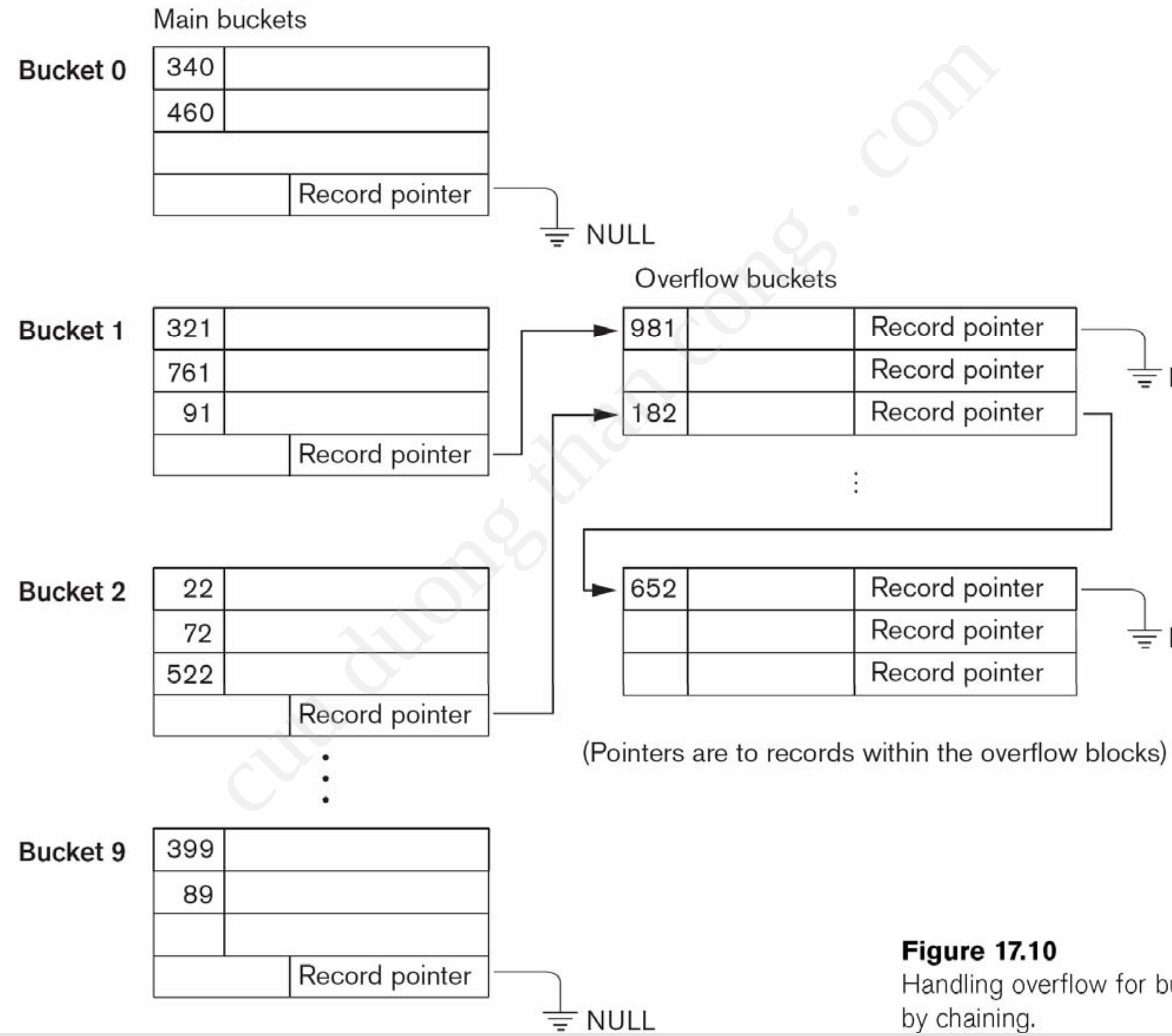


Figure 17.10
Handling overflow for buckets by chaining.

Hashed Files (cont.)

- To reduce overflow records, a hashed file is typically kept 70-80% full.
- The hash function *h* should distribute the records uniformly among the buckets; otherwise, search time will be increased because many overflow records will exist.

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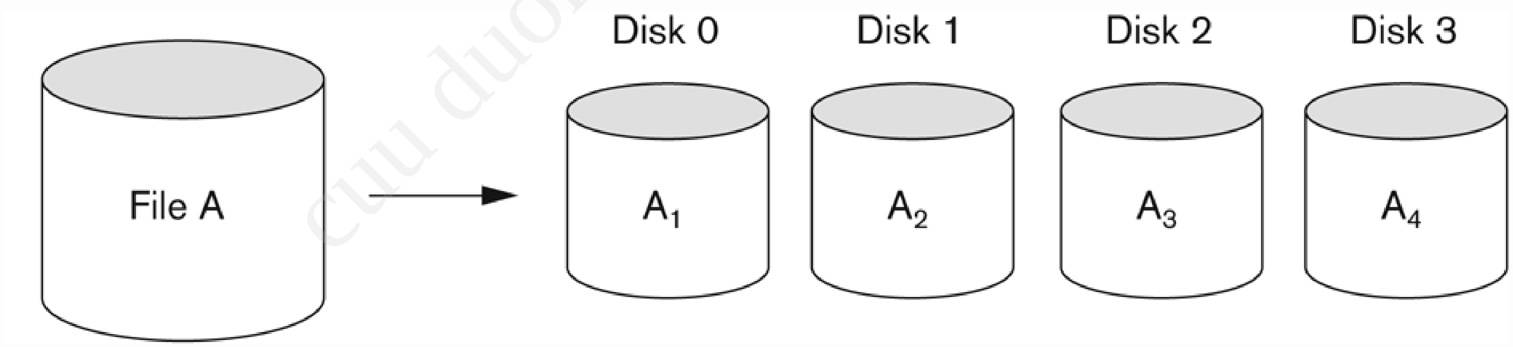
Parallelizing Disk Access using RAID Technology

- Secondary storage technology must take steps to keep up in performance and reliability with processor technology.
- A major advance in secondary storage technology is represented by the development of **RAID**, which originally stand for **Redundant Arrays of Inexpensive Disks.**
- **RAID**: is a data storage virtualization technology that combines multiple physical disk drive components into a single logical unit for the purposes of data redundancy, performance improvement, or both.

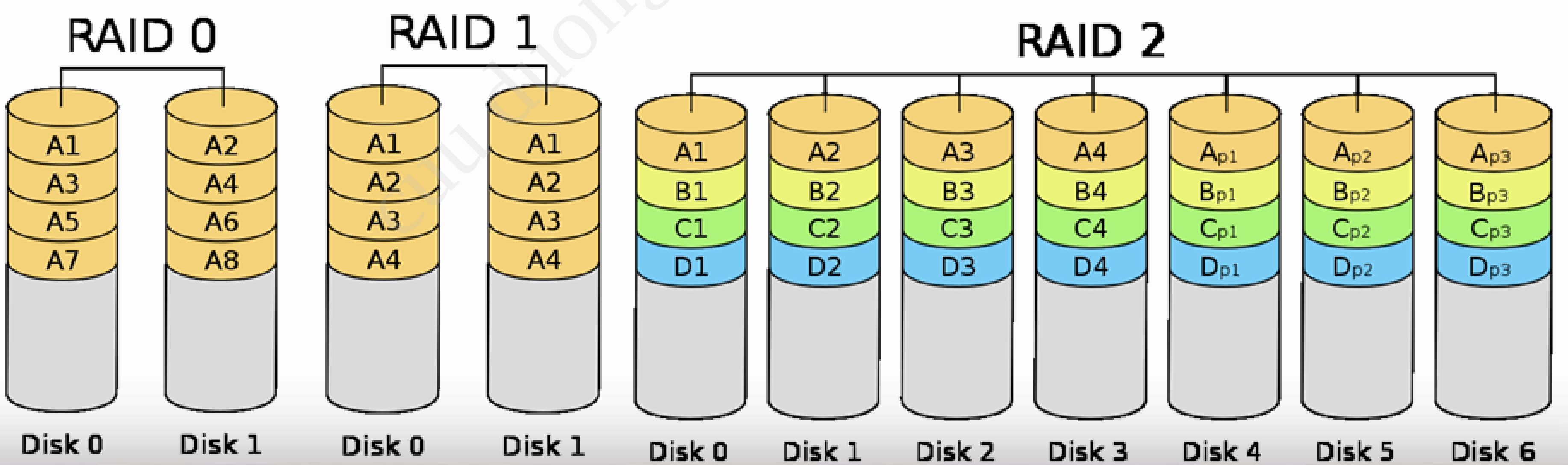
RAID Technology (cont.)

- A natural solution is a large array of small independent disks acting as a single higher-performance logical disk.
- A concept called **data striping** is used, which utilizes *parallelism* to improve disk performance.
- Data striping distributes data transparently over multiple disks to make them appear as a single large, fast disk.



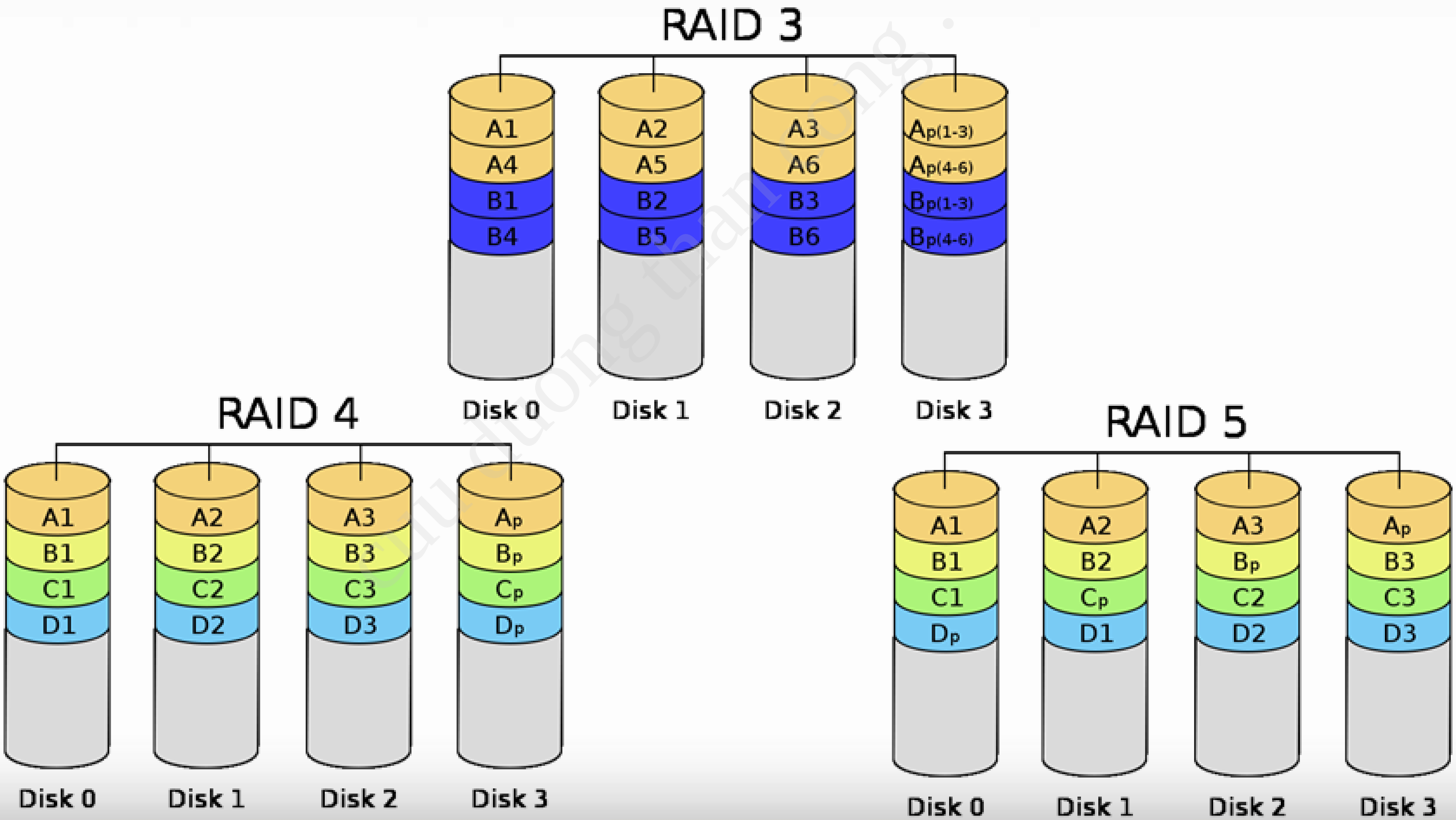
RAID Technology (cont.)

- Data is distributed across the drives in one of several ways, referred to as RAID levels, depending on the required level of redundancy and performance
  - **Raid level 0** has no redundant data and hence has the best write performance.
  - **Raid level 1** uses mirrored disks -> best read performance
  - **Raid level 2** uses bit-level striping memory-style redundancy by using Hamming codes, which contain parity bits for distinct overlapping subsets of components. Level 2 includes both error detection and correction.



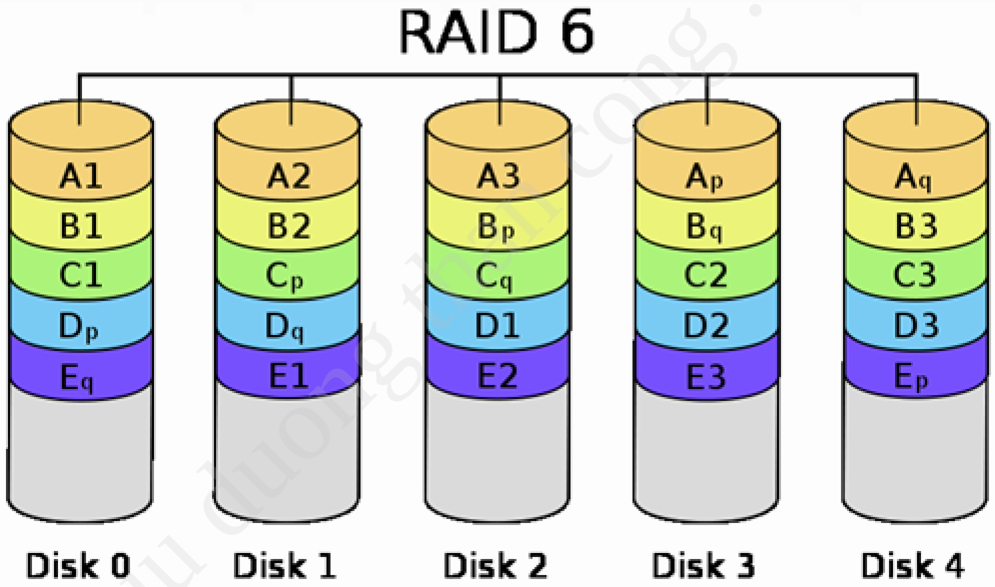
RAID Technology (cont.)

- **Raid level 3** uses byte-level striping and a single parity disk relying on the disk controller to figure out which disk has failed. Not commonly used in practice
- **Raid levels 4 and 5** use block-level data striping, with level 5 distributing data and parity information across all disks.



RAID Technology (cont.)

- **Raid level 6** applies the so-called *P* + *Q* redundancy scheme using Reed-Soloman codes to protect against up to two disk failures by using just two redundant disks.



Use of RAID Technology (cont.)

- Different raid organizations are being used under different situations:
  - Raid level 1 (mirrored disks) is the easiest for rebuild of a disk from other disks
    - It is used for critical applications like logs.
  - Raid level 2 uses memory-style redundancy by using Hamming codes, which contain parity bits for distinct overlapping subsets of components. Level 2 includes both error detection and correction.
  - Raid level 3 (single parity disks relying on the disk controller to figure out which disk has failed) and level 5 (block-level data striping) are preferred for large volume storage, with level 3 giving higher transfer rates.
  - Most popular uses of the RAID technology currently are: Level 0 (with striping), Level 1 (with mirroring) and Level 5 with an extra drive for parity.
  - Design decisions for RAID include – level of RAID, number of disks, choice of parity schemes, and grouping of disks for block-level striping.

Storage Area Networks

- The demand for higher storage has risen considerably in recent times.
- Organizations have a need to move from a static fixed data center oriented operation to a more flexible and dynamic infrastructure for information processing.
- Thus they are moving to a concept of Storage Area Networks (SANs).
  - In a SAN, online storage peripherals are configured as nodes on a high-speed network and can be attached and detached from servers in a very flexible manner.
- This allows storage systems to be placed at longer distances from the servers and provide different performance and connectivity options.

Storage Area Networks (contd.)

- **Advantages of SANs are:**
  - Flexible many-to-many connectivity among servers and storage devices using fiber channel hubs and switches.
  - Up to 10km separation between a server and a storage system using appropriate fiber optic cables.
  - Better isolation capabilities allowing nondisruptive addition of new peripherals and servers.
- SANs face the problem of combining storage options from multiple vendors and dealing with evolving standards of storage management software and hardware.

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Indexes as Access Paths

- A single-level index is an auxiliary file that makes it more efficient to search for a record in the data file.
- The index is usually specified on one field of the file (although it could be specified on several fields)
- One form of an index is a file of entries <**field value, pointer to record>**, which is ordered by field value
- The index is called an access path on the field.

Indexes as Access Paths (cont.)

- The index file usually occupies considerably less disk blocks than the data file because its entries are much smaller.
- A binary search on the index yields a pointer to the file record.
- Indexes can also be characterized as dense or sparse:
  - A **dense index** has an index entry for every search key value (and hence every record) in the data file.
  - A **sparse (or nondense) index**, on the other hand, has index entries for only some of the search values

Types of Single-level Ordered Indexes

- Primary Indexes
- Clustering Indexes
- Secondary Indexes

Primary Index

- Defined on an **ordered data file.**
  - The data file is ordered on a ***key field***.
- One index entry *for each block* in the data file
  - *First record* in the block, which is called the *block anchor*
- A similar scheme can use the *last record* in a block.

Index file
(<*K(i)*, *P(i)*> entries)

Primary key value	Block pointer
1	
4	
8	
12	

Primary key field

ID	Name	DoB	Salary	Sex
1				
2				
3				
4				
6				
7				
8				
9				
10				
12				
13				
15				

Primary Index

- Number of index entries?
  - Number of blocks in data file.
- Dense or Nondense?
  - Nondense
- Search/ Insert/ Update/ Delete?

Clustering Index

- Defined on an **ordered data file**
  - The data file is ordered on a *non-key field*
- One index entry for *each distinct value* of the field
  - The index entry points to the *first data block* that contains records with that field value

Clustering field

Index file

(<*K(i)*, *P(i)*> entries)

Clustering field value	Block pointer
1	
2	
3	
4	
5	

Dept_No	Name	DoB	Salary	Sex
1				
1				
2				
2				
2				
2				
2				
3				
3				
4				
4				
5				

Clustering field

Index file

(<*K(i)*, *P(i)*> entries)

Clustering field value	Block pointer
1	
2	
3	
4	
5	

Dept_No	Name	DoB	Salary	Sex
1				
1				
2				
2				
2				
2				
2				
3				
3				
4				
4				
5				

Clustering Index

- Number of index entries?
  - Number of distinct indexing field values in data file.
- Dense or Nondense?
  - Nondense
- Search/ Insert/ Update/ Delete?

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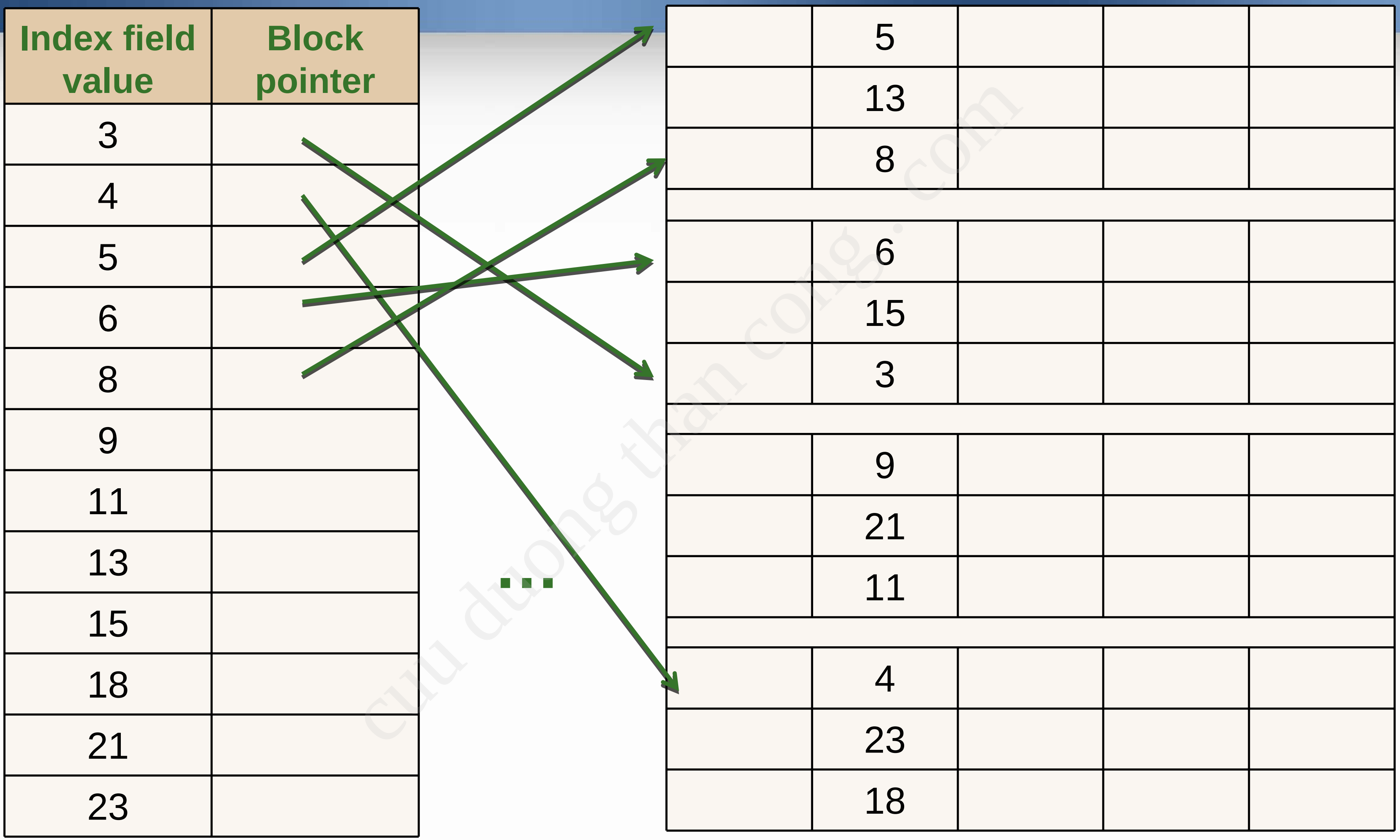
Secondary Index

- A secondary index provides a secondary means of accessing a file beside the primary access path**.**
  - The data file is unordered on indexing field*.*
- Indexing field:
  - secondary key (unique value)
  - nonkey (duplicate values)
- The index is an ordered file with two fields.
  - The first field: *indexing field.*
  - The second field: *block* pointer or *record* pointer.
- There can be ***many*** secondary indexes for the same file.

Index file
(<*K(i)*, *P(i)*> entries)

Secondary key field



Secondary index on key field

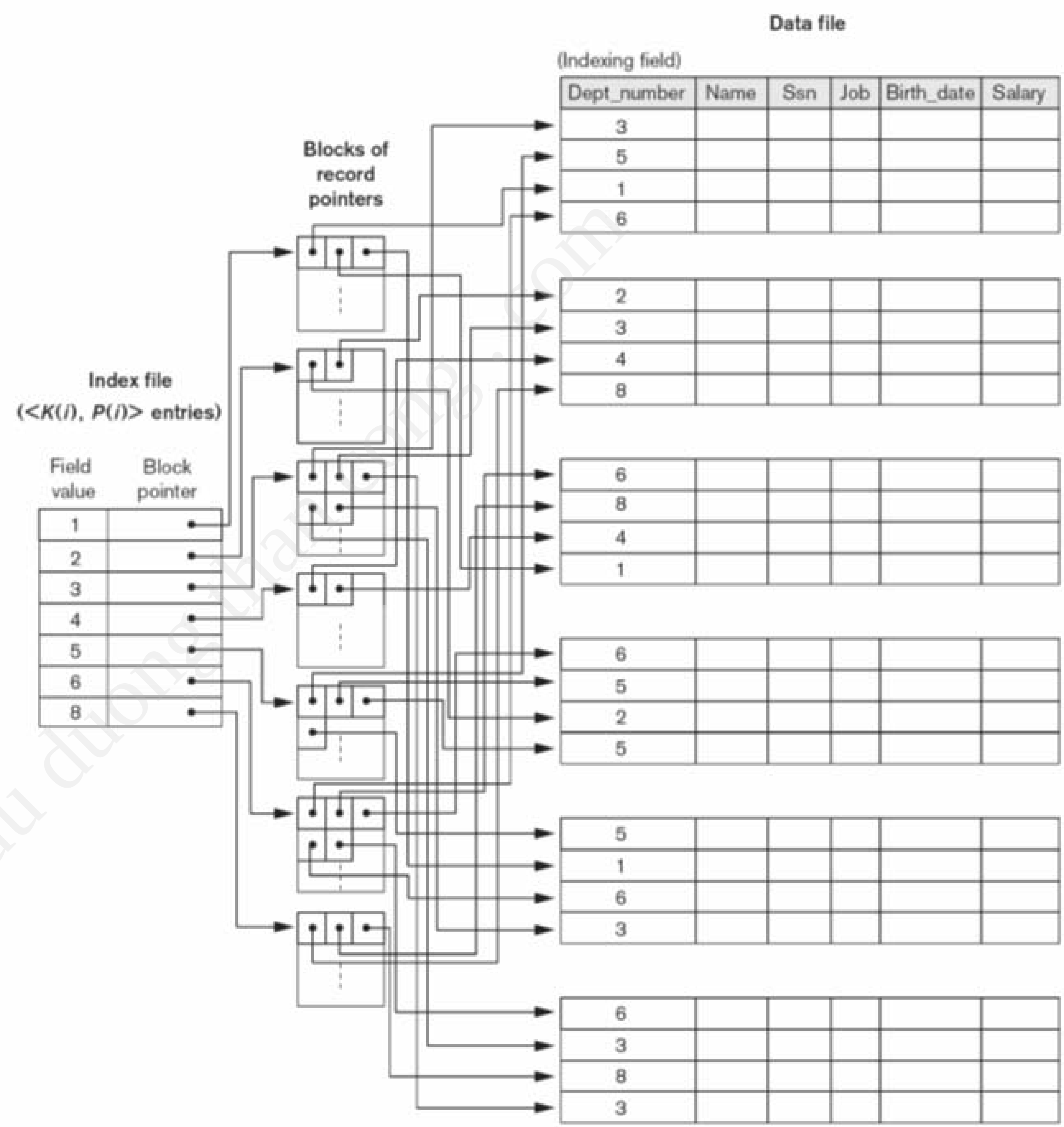
Secondary Index on Key Field

- Number of index entries?
  - Number of record in data file
- Dense or Nondense?
  - Dense
- Search/ Insert/ Update/ Delete?

Secondary Index on non-Key Field

- **Discussion:** Structure of Secondary index on non-key field?
- Option 1: include **duplicate index entries** with the same *K*(*i*) value - one for each record.
- Option 2: keep a **list of pointers** <*P*(*i*, 1), ..., *P*(*i*, *k*)> in the index entry for *K*(*i*).
- Option 3:
  - more commonly used.
  - one entry for each *distinct index field value* + *an* **extra level of indirection** to handle the multiple pointers.

- Secondary Index on non-key field:
  Option 3



Secondary Index on non-Key Field

- Number of index entries?
  - Number of records in data file
  - Number of distinct index field values
- Dense or Nondense?
  - Dense/ Nondense
- Search/ Insert/ Update/ Delete?

Summary of Single-level Indexes

- Ordered file on indexing field?
  - Primary index
  - Clustering index
- Indexing field is Key?
  - Primary index
  - Secondary index
- Indexing field is not Key?
  - Clustering index
  - Secondary index

Summary of Single-level Indexes

- Dense index?
  - Secondary index
- Nondense index?
  - Primary index
  - Clustering index
  - Secondary index

Summary of Single-level Indexes

Table 18.2 Properties of Index Types

Type of Index	Number of (First-level) Index Entries	Dense or Nondense (Sparse)	Block Anchoring on the Data File
Primary	Number of blocks in data file	Nondense	Yes
Clustering	Number of distinct index field values	Nondense	Yes/no[a]
Secondary (key)	Number of records in data file	Dense	No
Secondary (nonkey)	Number of records[b] or number of distinct index field values[c]	Dense or Nondense	No

[a] Yes if every distinct value of the ordering field starts a new block; no otherwise.
[b] For option 1.
[c] For options 2 and 3.

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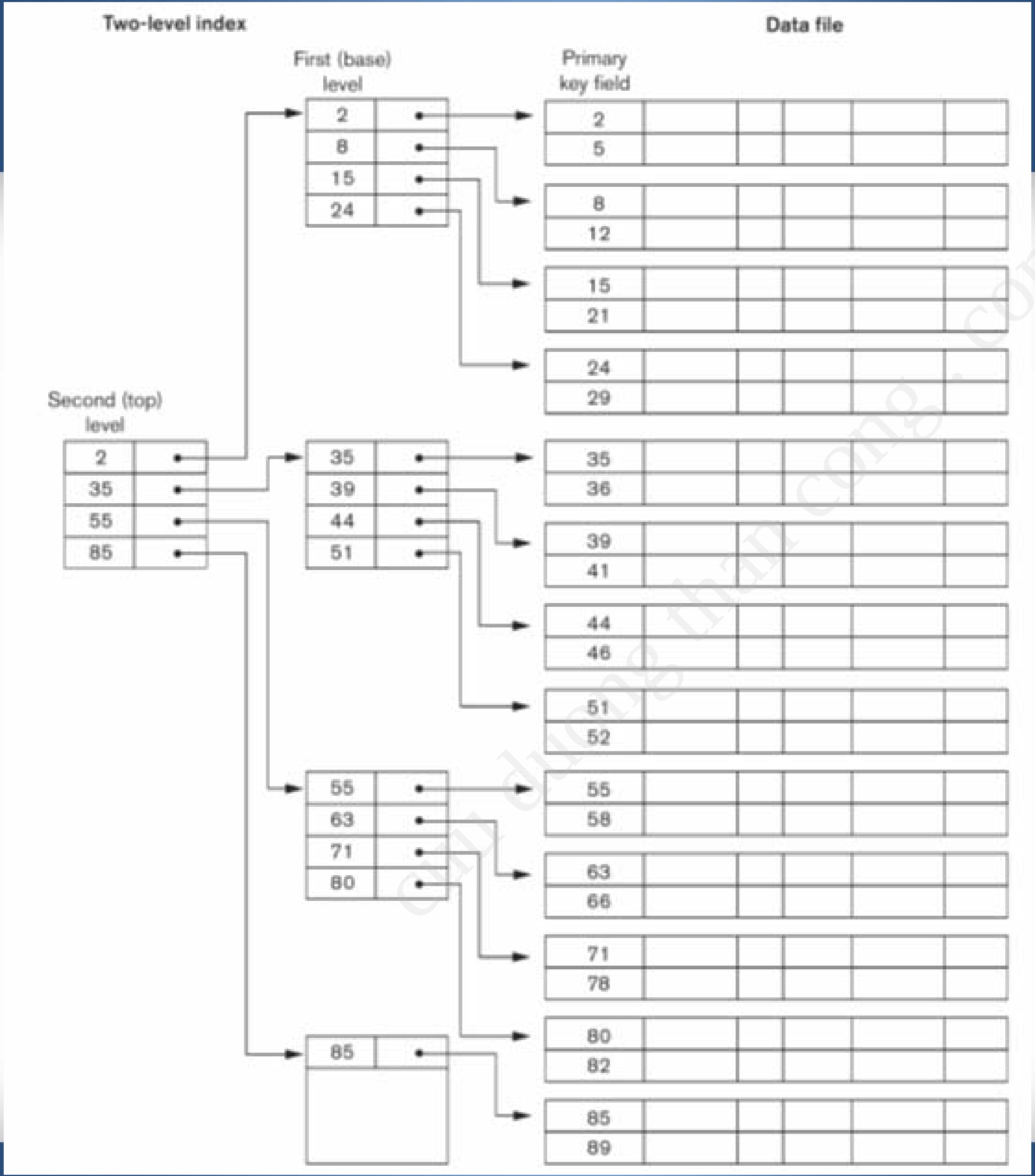
Multi-Level Indexes

- Because a single-level index is an ordered file, we can **create a primary index *to the index itself***.
  - The original index file is called the *first-level index* and the index to the index is called the *second-level index.*
- We can repeat the process, creating a third, fourth, ..., top level **until all entries of the *top level* fit in one disk block.**
- A multi-level index can be created for any type of first-level index (primary, secondary, clustering) as long as the first-level index consists of *more than one* disk block.

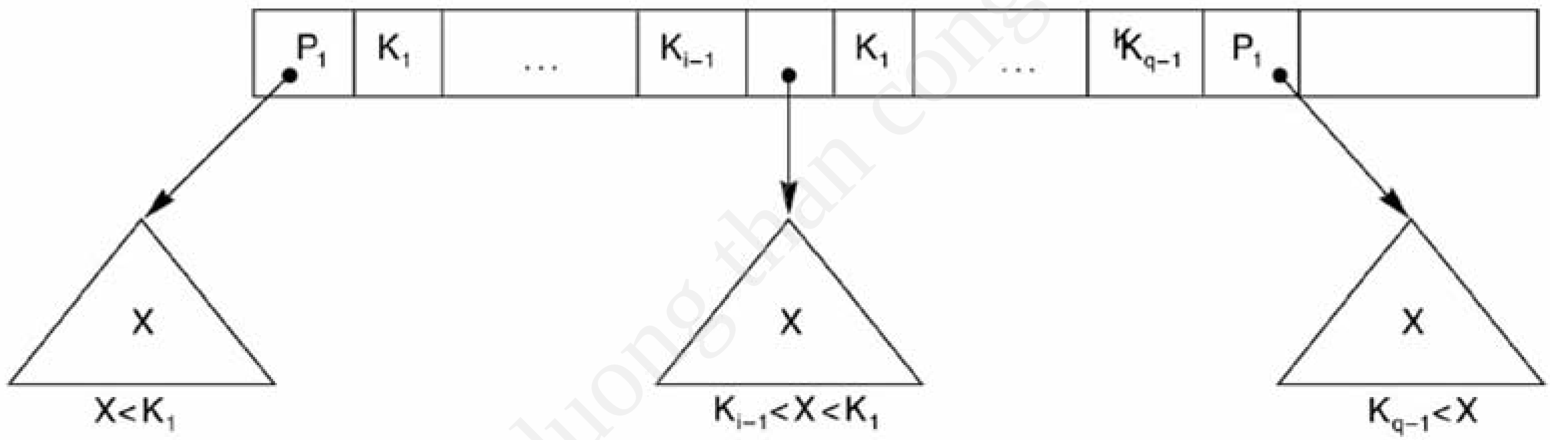


A two-level primary index resembling ISAM (Indexed Sequential Access Method) organization.

Multi-Level Indexes

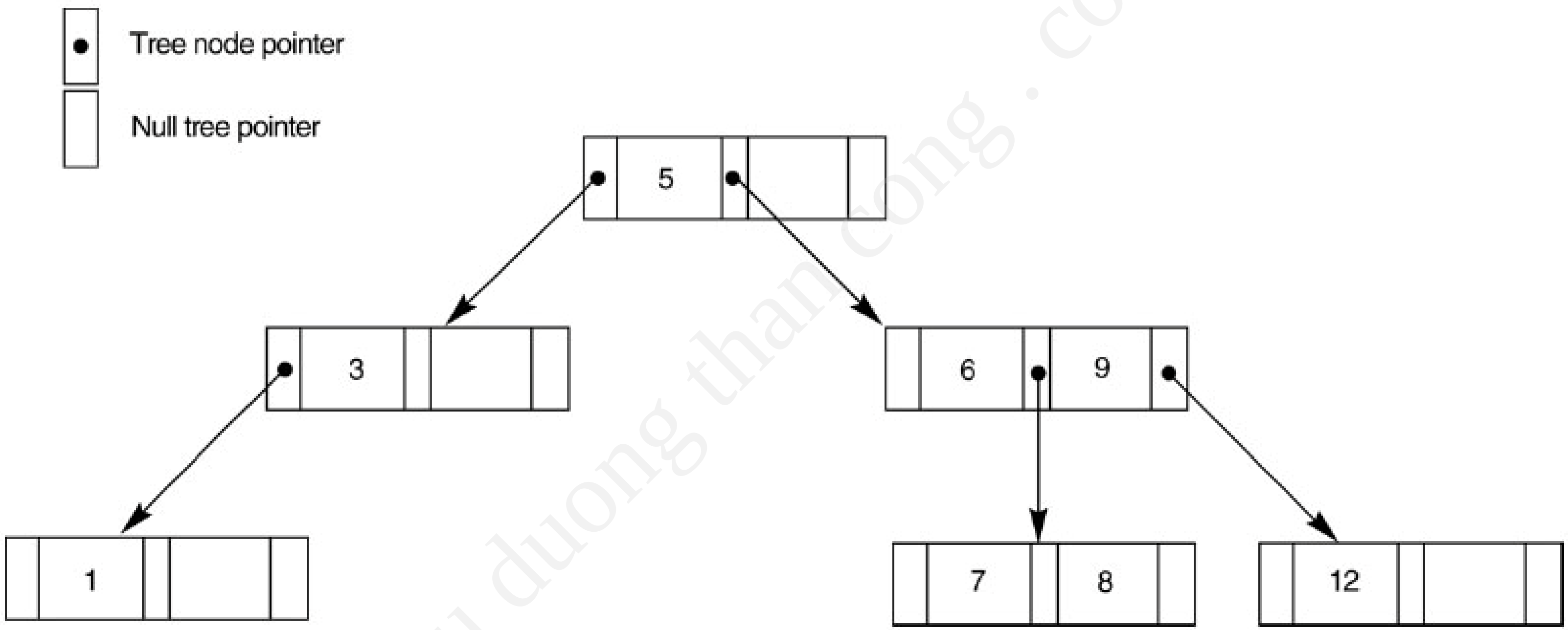
- Such a multi-level index is a form of *search tree*.
- However, insertion and deletion of new index entries is a severe problem because every level of the index is an *ordered file.*

Search Tree



Search Tree with Pointers to Subtrees below It trees below It

A Search Tree of Order p = 3



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Dynamic Multilevel Indexes

- Most multi-level indexes use **B-tree** or **B+-tree** data structures because of the insertion and deletion problem.
    - This leaves space in each tree node (disk block) to allow for new index entries
- These data structures are variations of search trees that allow efficient insertion and deletion of new search values.
- In B-Tree and B+-Tree data structures, each node corresponds to a disk block.
- Each node is kept between half-full and completely full.

Dynamic Multilevel Indexes

- An insertion into a node that is not full is quite efficient
  - If a node is full, the insertion causes a split into two nodes
- Splitting may propagate to other tree levels
- A deletion is quite efficient if a node does not become less than half full
- If a deletion causes a node to become less than half full, it must be merged with neighboring nodes

Difference between B-tree and B+-tree

- In a B-Tree, pointers to data records exist at all levels of the tree.
- In a B^+-Tree, all pointers to data records exist at the leaf-level nodes.
- A B^+-Tree can have less levels (or higher capacity of search values) than the corresponding B-tree.

B-tree Structures

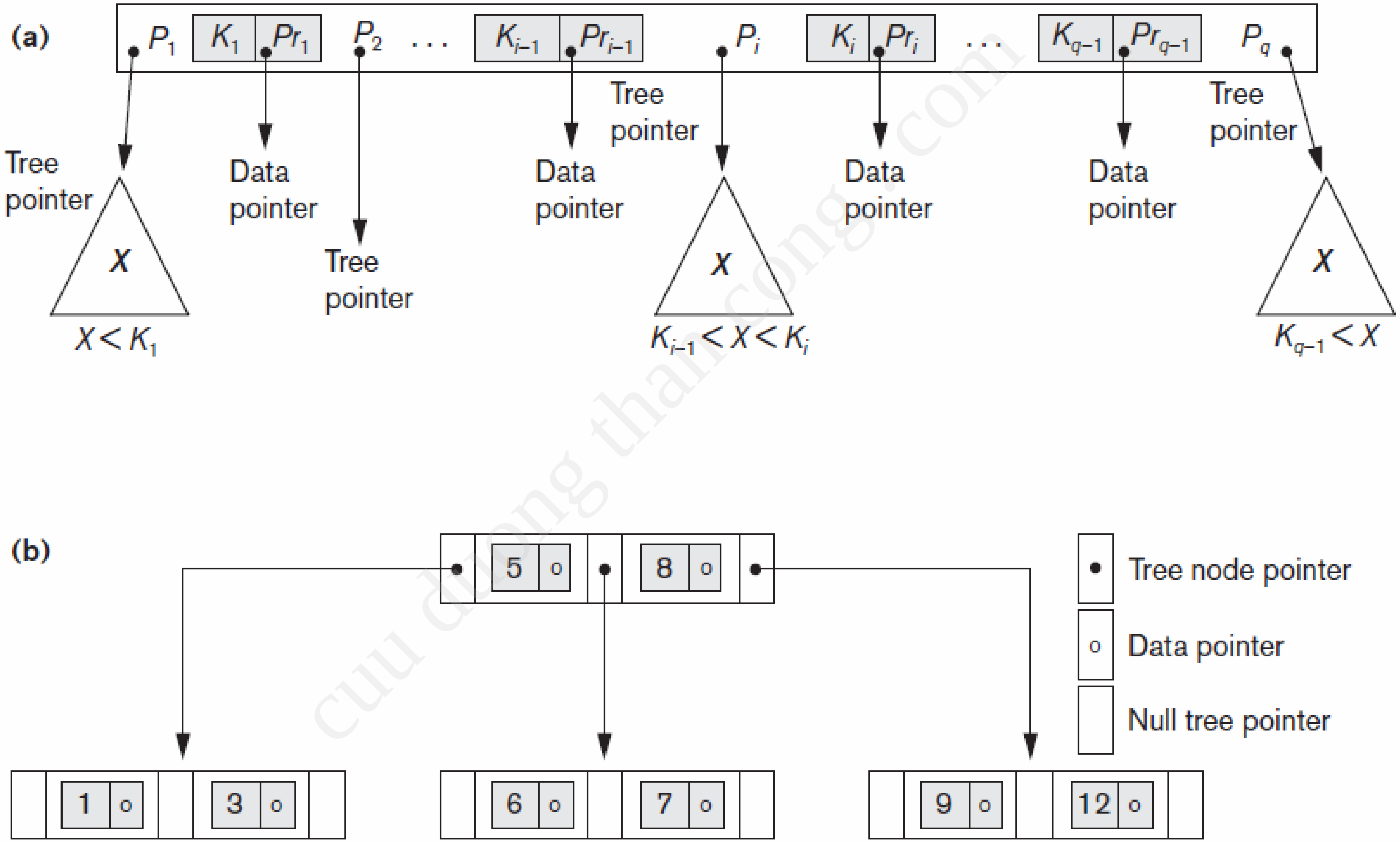


Figure 18.10
B-tree structures. (a) A node in a B-tree with $q - 1$ search values. (b) A B-tree of order $p = 3$. The values were inserted in the order 8, 5, 1, 7, 3, 12, 9, 6.

The Nodes of a B^+-Tree

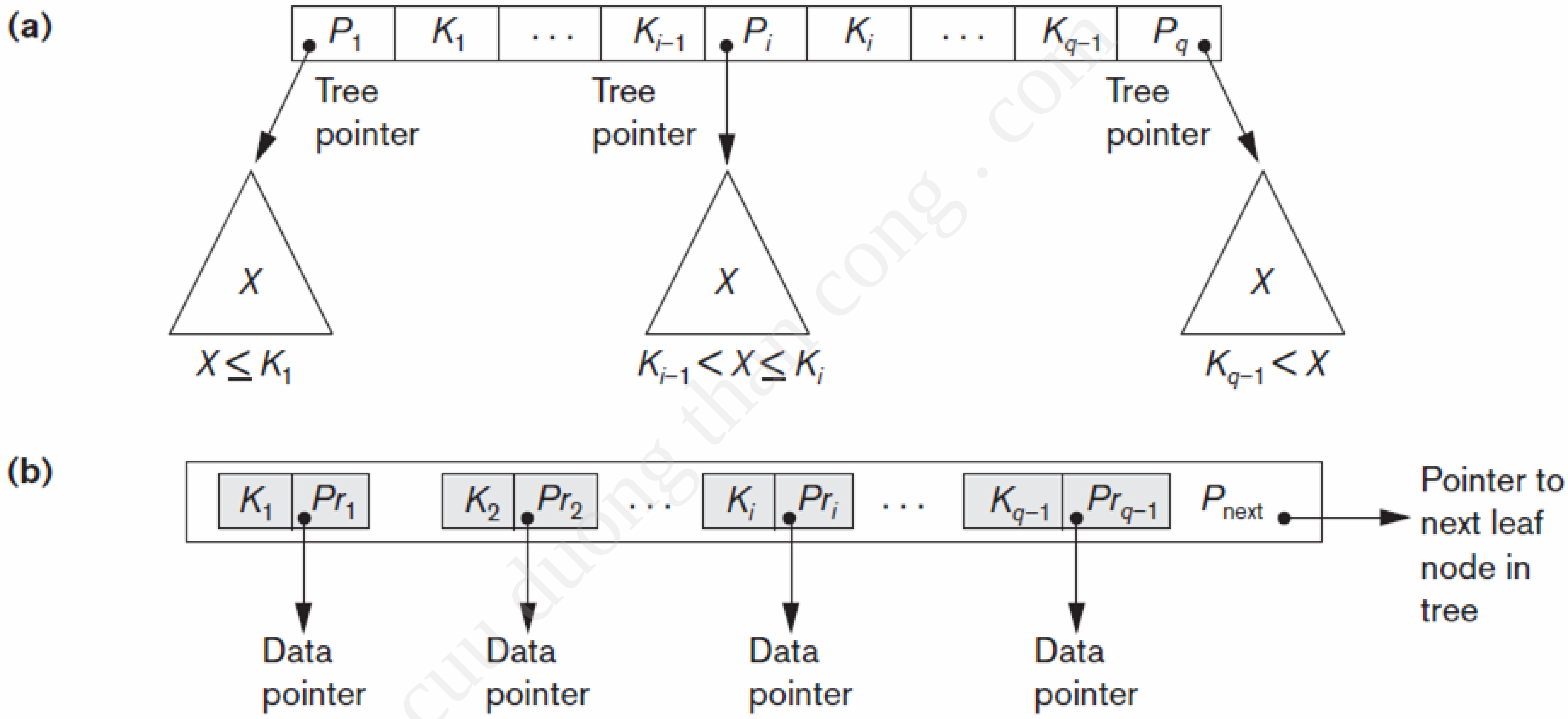
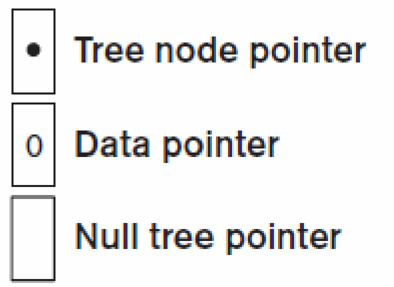


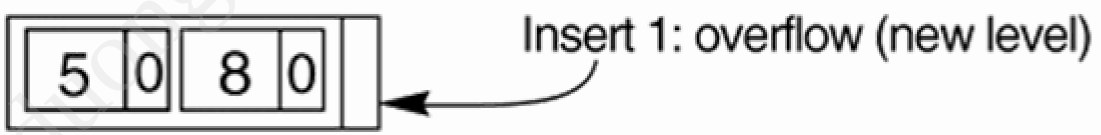
Figure 18.11
The nodes of a B^+-tree. (a) Internal node of a B^+-tree with $q - 1$ search values.
(b) Leaf node of a B^+-tree with $q - 1$ search values and $q - 1$ data pointers.

Example of insertion in B+-Tree

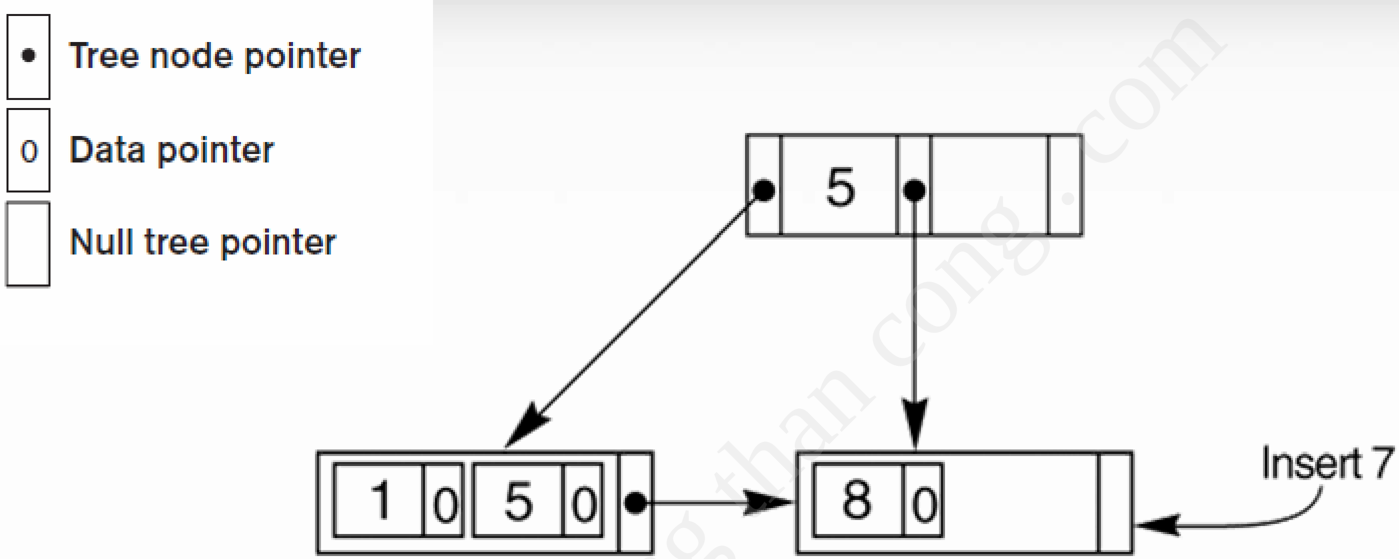


p = 3 and p_{leaf} = 2

Insertion Sequence: *8, 5,* 1, 7, 3, 12, 9, 6

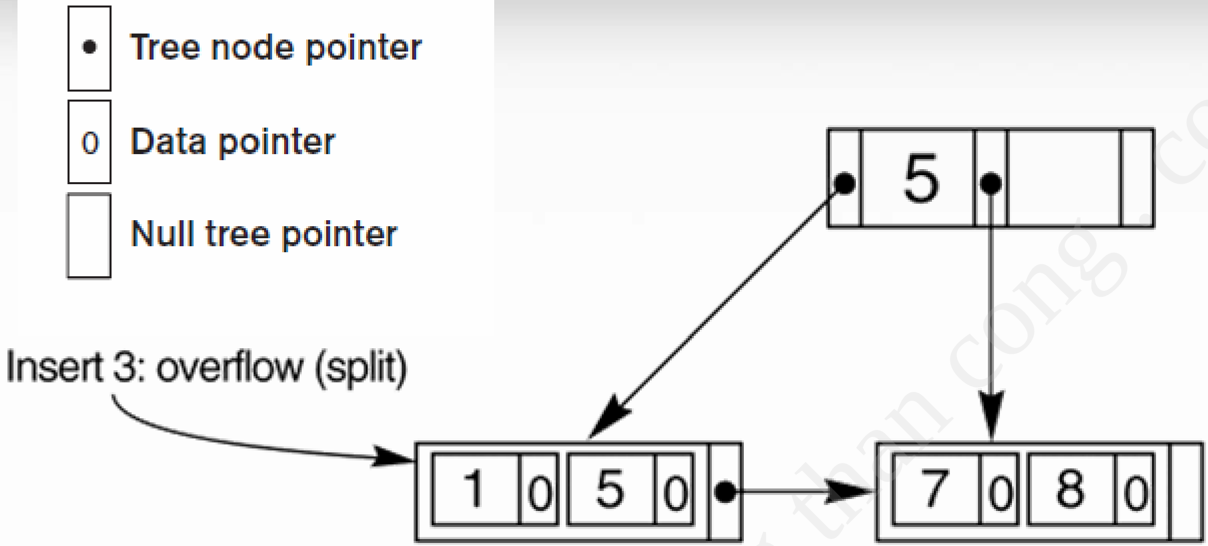


Example of insertion in B+-Tree



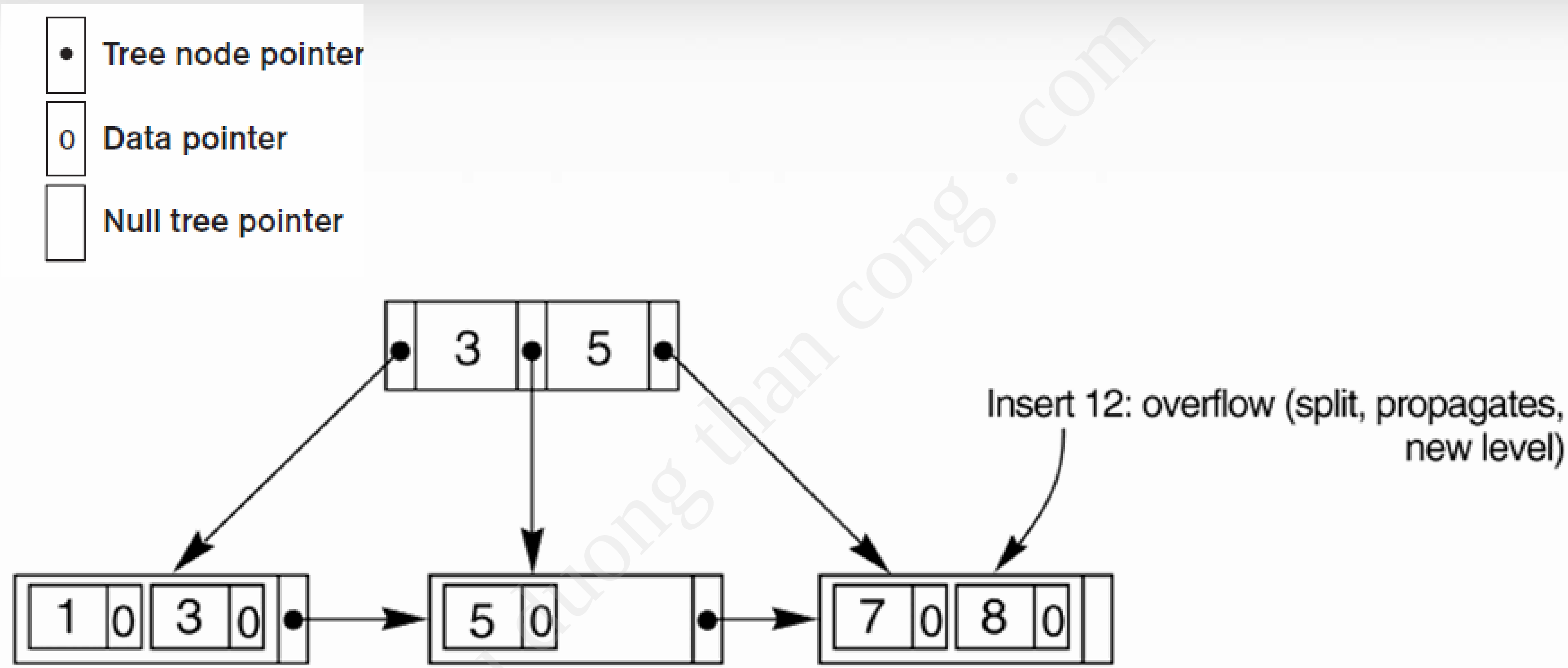
Insertion Sequence: *8, 5, 1,* 7, 3, 12, 9, 6

Example of insertion in B$^+$-Tree



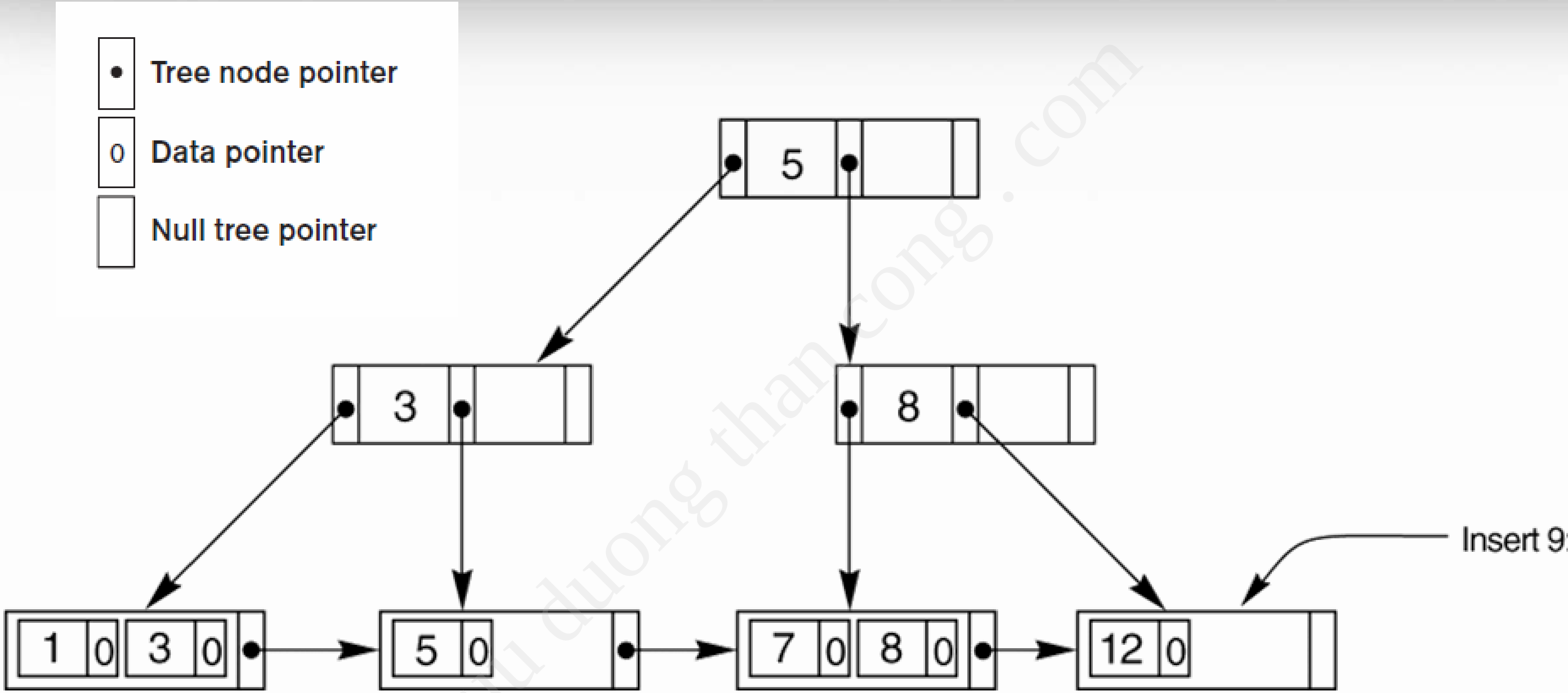
Insertion Sequence: *8, 5, 1, 7,* 3, 12, 9, 6

Example of insertion in B^+-Tree



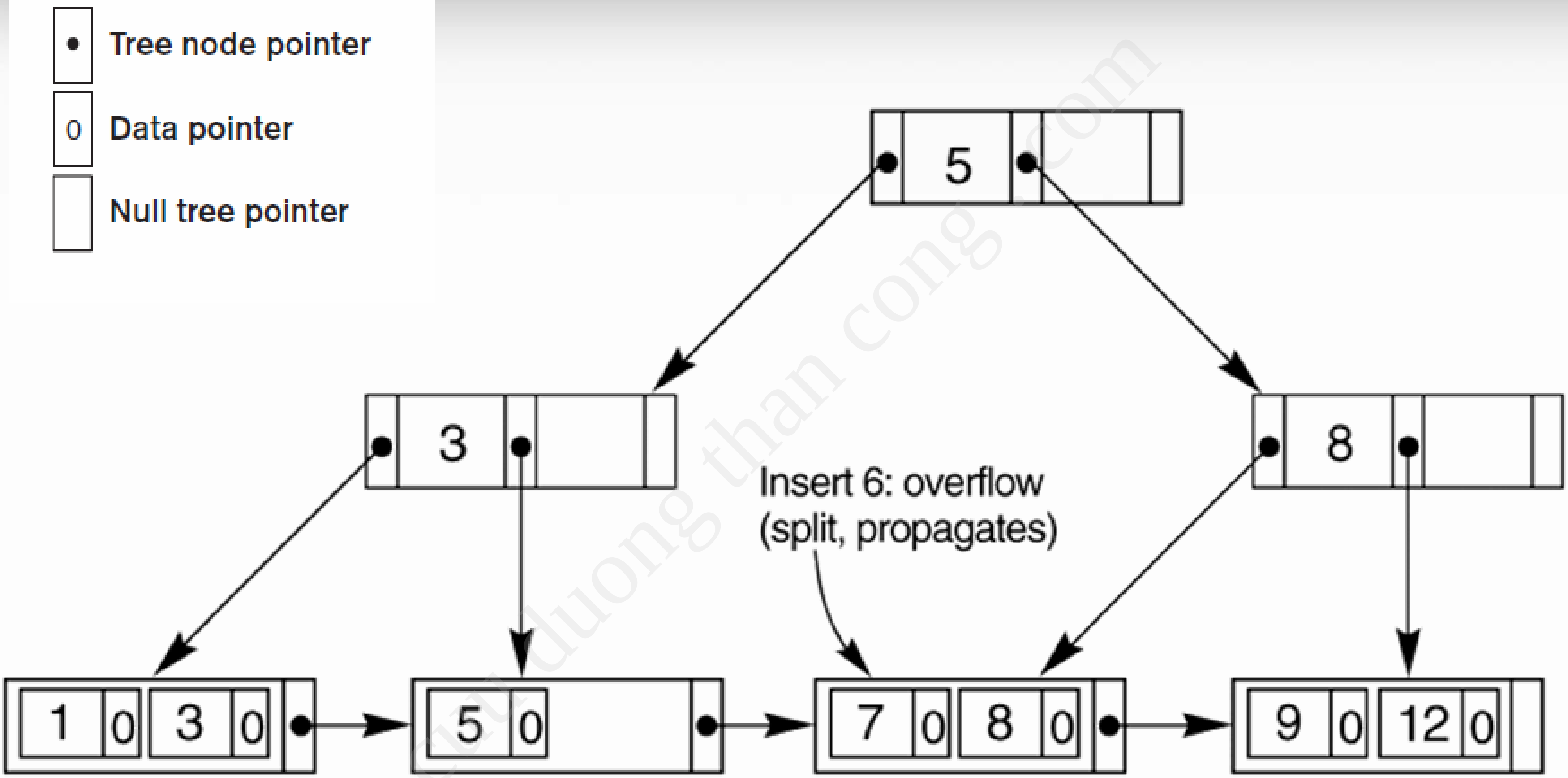
Insertion Sequence: *8, 5, 1, 7, 3,* 12, 9, 6

Example of insertion in B$^+$-Tree



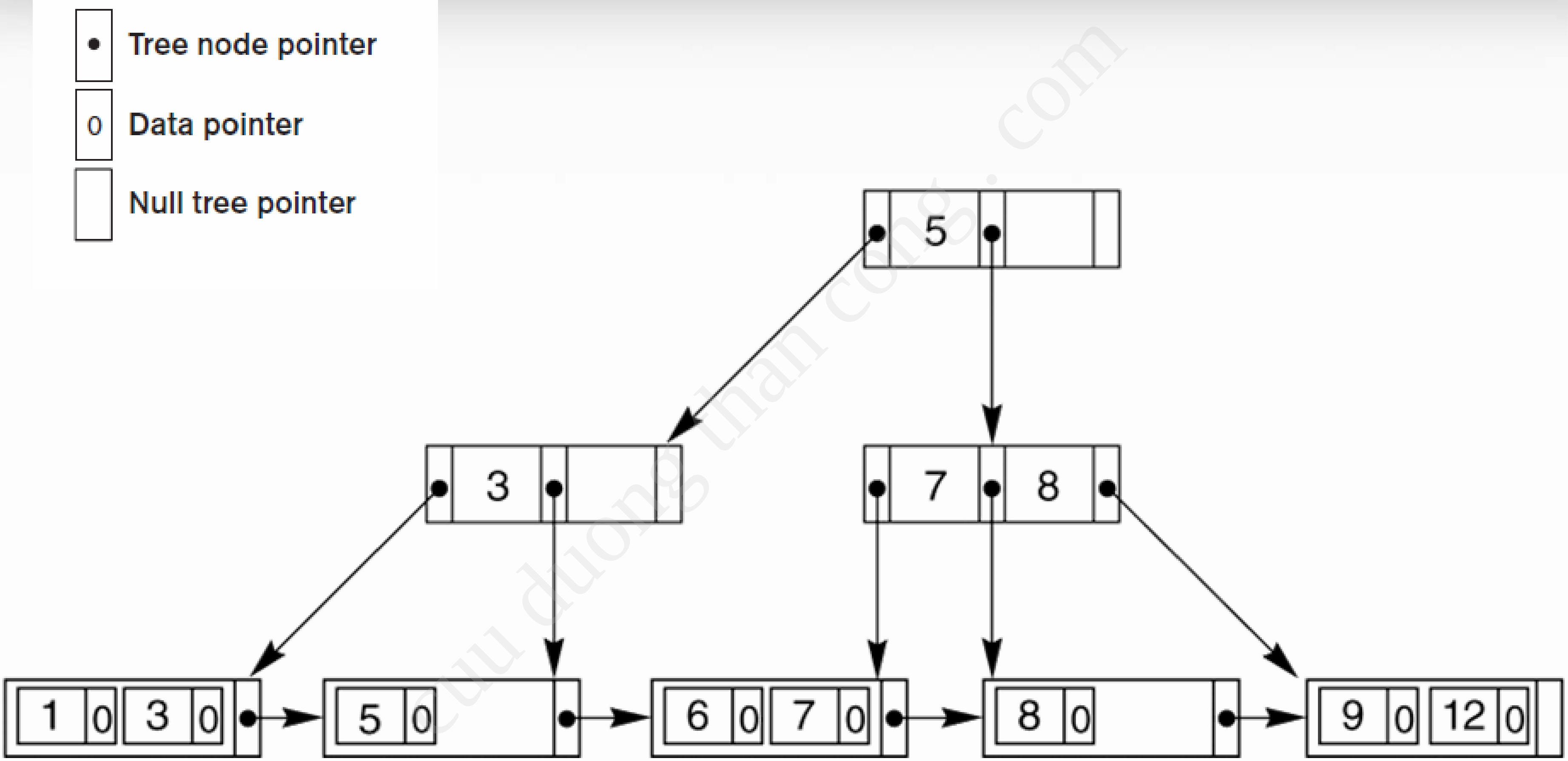
Insertion Sequence: *8, 5, 1, 7, 3, 12,* 9, 6

Example of insertion in B^+-Tree



Insertion Sequence: *8, 5, 1, 7, 3, 12, 9,* 6

Example of insertion in B+-Tree



Insertion Sequence: *8, 5, 1, 7, 3, 12, 9, 6*

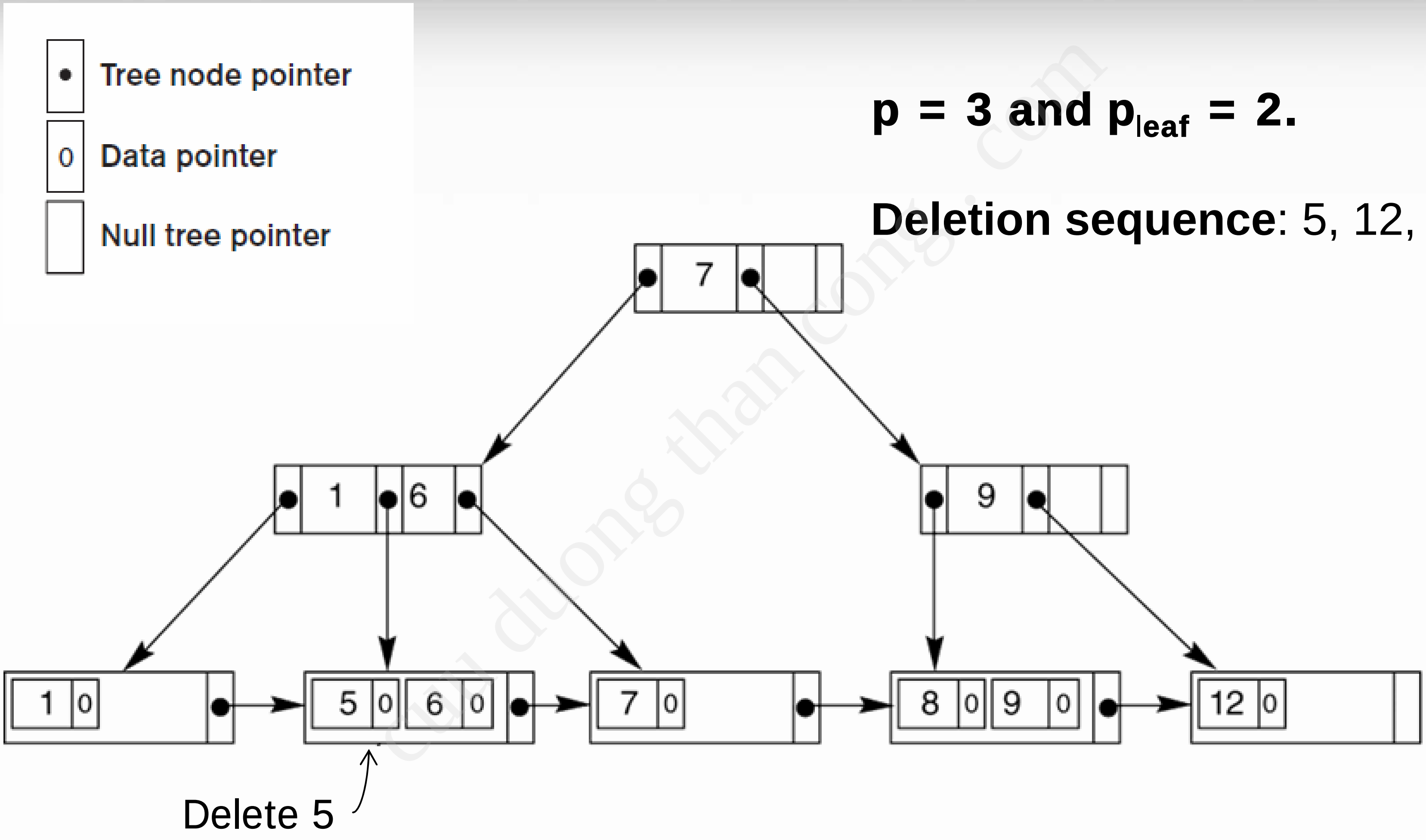
B^+-Tree: Delete entry

- Start at root, find leaf L where entry belongs.
- Remove the entry.
  - If L is at least half-full, done!
  - If L has fewer entries than it should,
    - Try to re-distribute, borrowing from sibling (adjacent node with same parent as L).
    - If re-distribution fails, merge L and sibling.
- If merge occurred, must delete entry (pointing to L or sibling) from parent of L.
- Merge could propagate to root, decreasing height.

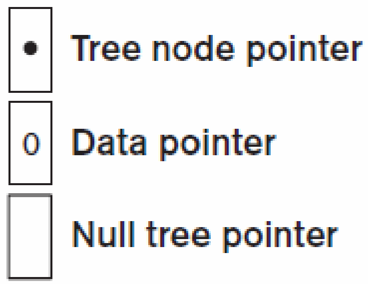
Example of deletion from B$^+$-Tree

p = 3 and p_{leaf} = 2.

Deletion sequence: 5, 12, 9

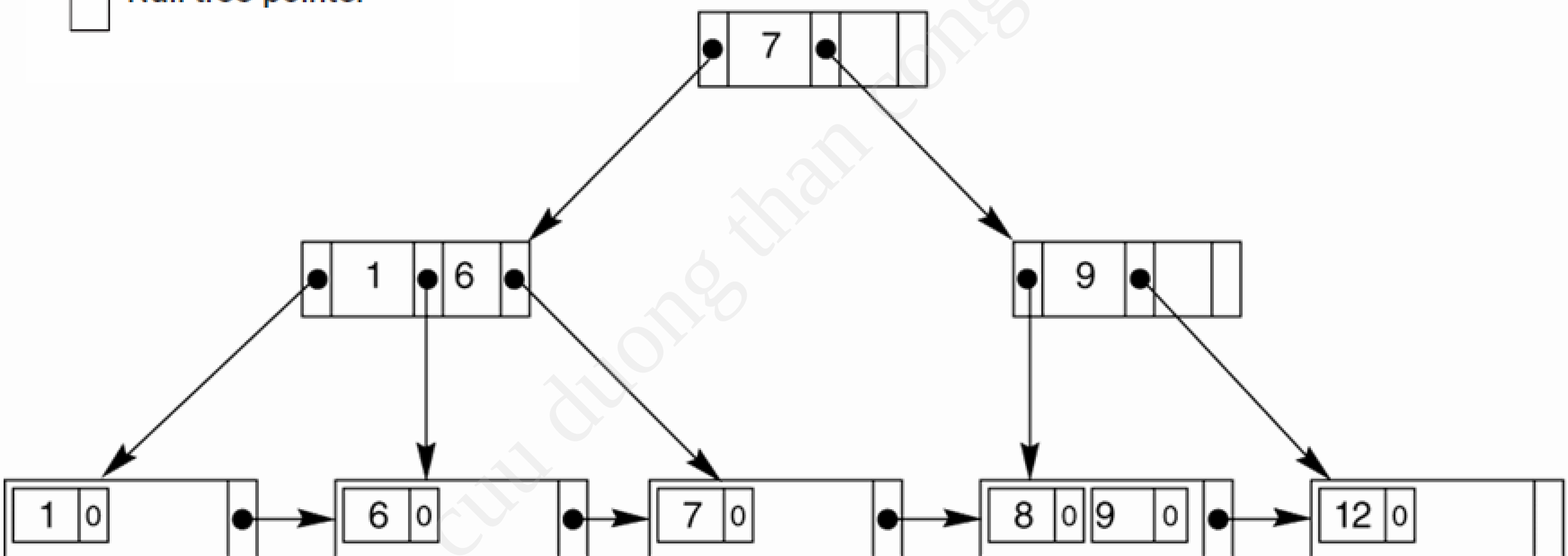


Example of deletion from B+-Tree (cont.)



p = 3 and p_{leaf} = 2.

Deletion sequence: 5, 12, 9

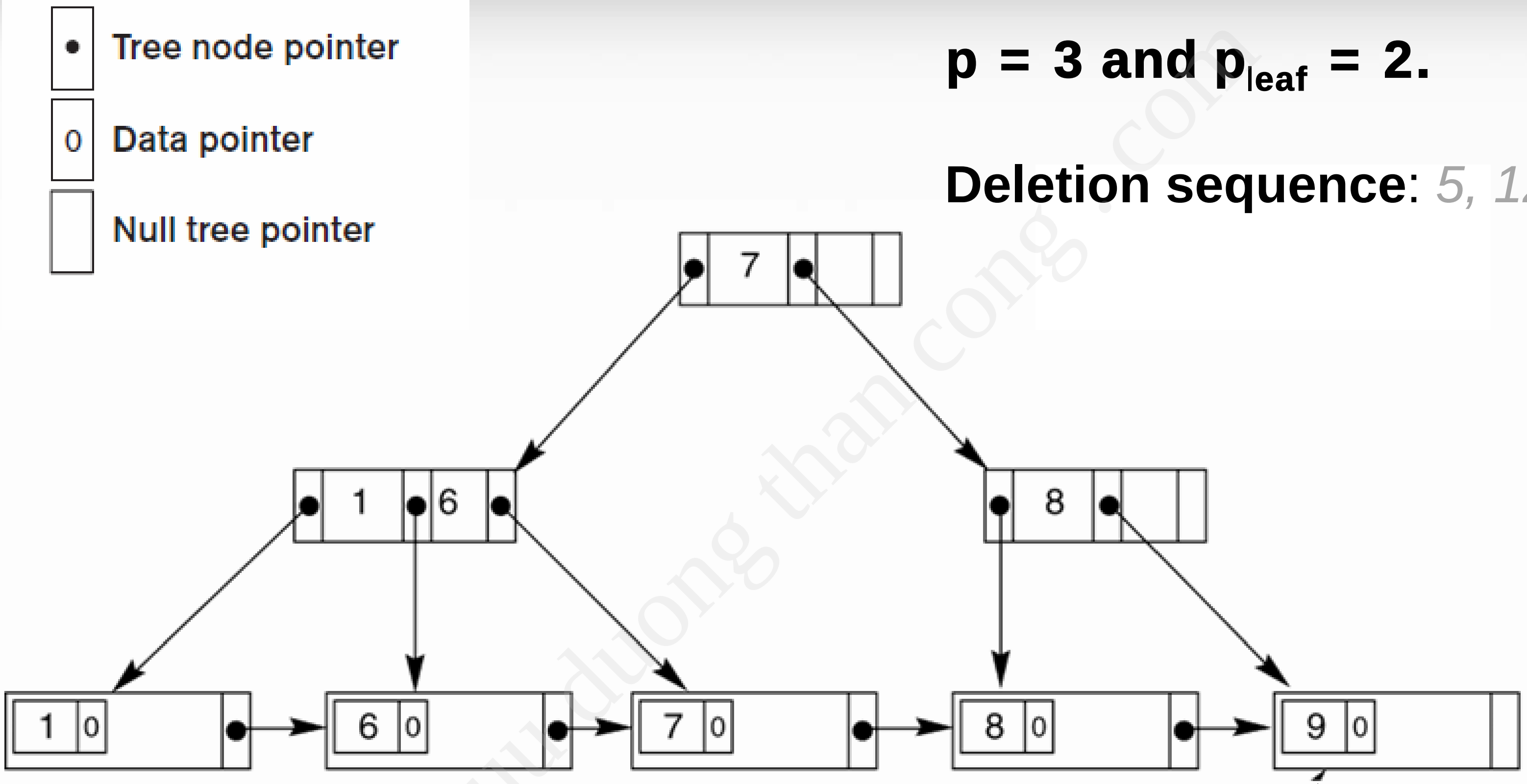


Delete 12: **underflow (redistribute)**

Example of deletion from B+-Tree (cont.)

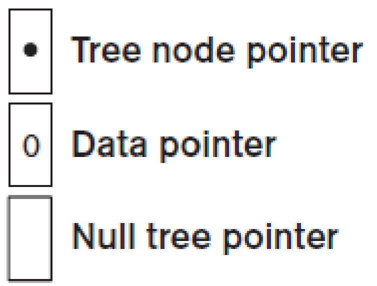
$p = 3$ and $p_{leaf} = 2$.

Deletion sequence: 5, 12, 9



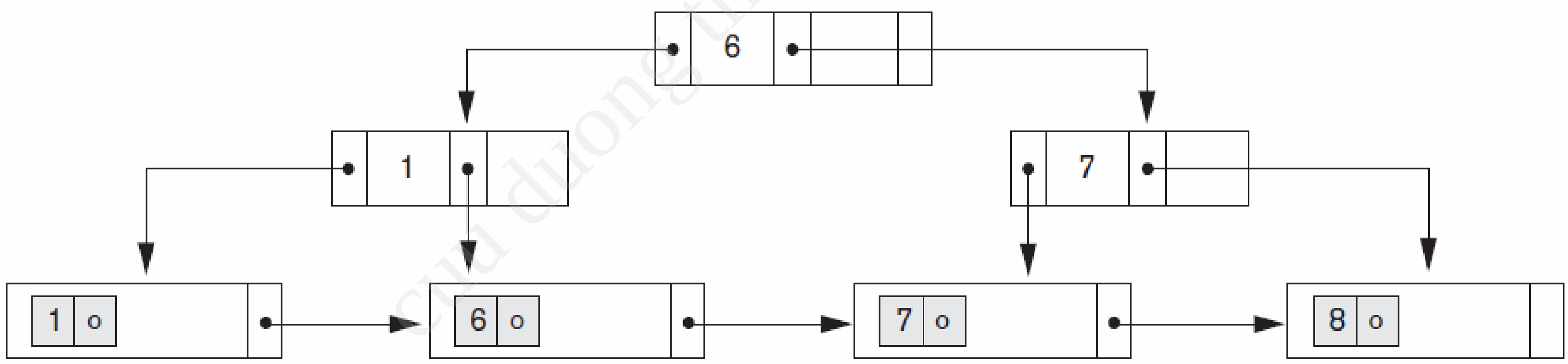
Delete 9:
Underflow (merge with left, redistribute)

Example of deletion from B^+-Tree (cont.)



$p = 3$ and $p_{leaf} = 2$.

Deletion sequence: *5, 12, 9*



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