Carving Database Storage to Detect and Trace Security Breaches

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Database Attacks by Privileged Users

- Sensitive data is commonly stored in Database Management Systems(DBMS)
  - Social Networks (e.g., Facebook or Twitter)
  - Ecommerce (e.g., Uber)
  - Media (e.g., Netflix or Spotify)
  - Banks (e.g., JP Morgan Chase)
  - Healthcare (e.g., Bayer)
  - Government (e.g., IL Department of Revenue)
- How do you protect your database against insider attacks?

Motivation: Malicious Administrators

Security Approaches Against Insiders

- Defense (e.g., access control) vs. Detection (e.g., audit logs)
- DBMSes maintain a history of SQL queries in an audit log.
- DBMSes can't guarantee that audits logs are accurate.

Reliability of DBMS Audit Logs

- Log integrity verification with 3rd party tools
- What if logging was disabled?
  - DBAs have the legitimate privilege to disable logging.

Goal: Detect activity missing from log files.

- This will be done by carving storage artifacts.

Malicious DBA Example

1. Alex is a DBA for a government agency that keeps track of criminal records.

DBA

Database Storage

Del. Flag	Page Type: Table Table: CrimeReport
✓	Jonathan, 2005, piracy
✓	Karen, 2007, fraud
✓	Boris, 2012, shoplifting

Audit Log File

```
T1, INSERT INTO CrimeReport
      VALUES ('Jonathan', 2005, 'piracy');
T2, INSERT INTO CrimeReport
      VALUES ('Karen', 2007, 'fraud');
T3, UPDATE CrimeReport
      SET Crime = 'shoplifting'
      WHERE Name = 'Boris';
```

Malicious DBA Example

2. Jonathan tells Alex he'll pay him to erase his criminal record.

Criminal

DBA

Database Storage

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Audit Log File

```
T1, INSERT INTO CrimeReport
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      SET Crime = 'shoplifting'
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```

Malicious DBA Example

3. Alex agrees to accept Jonathan’s bribe.
   A. Disables logging
   B. Deletes Jonathan’s criminal record
   C. Re-enables logging

Malicious DBA

Database Storage

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Audit Log File

```
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T3, UPDATE CrimeReport
      SET Crime = ‘shoplifting’
      WHERE Name = ‘Boris’;
```

Malicious DBA Example

4. No one is aware that Jonathan's criminal history has been deleted.
    - No evidence in the audit log
    - Deleted records can not be queried. Example:

SELECT *
~~FROM~~ CrimeReport
WHERE *Record IS Deleted*

Good Citizen

Database Storage

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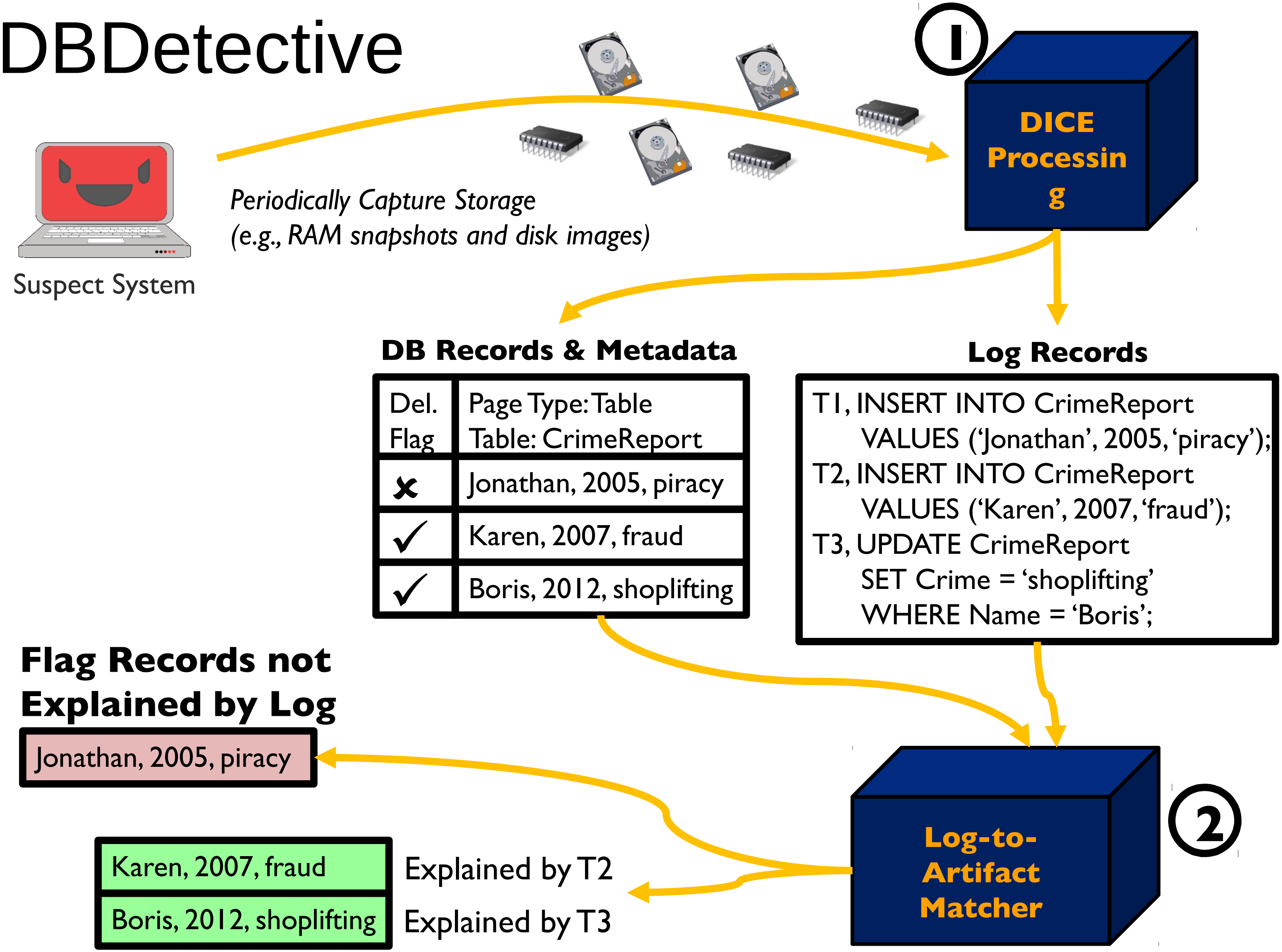
DBDetective



Periodically Capture Storage
(e.g., RAM snapshots and disk images)

DICE
Processin
g

DB Records & Metadata

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Log Records

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      SET Crime = 'shoplifting'
      WHERE Name = 'Boris';
```

Log-to-
Artifact
Matcher

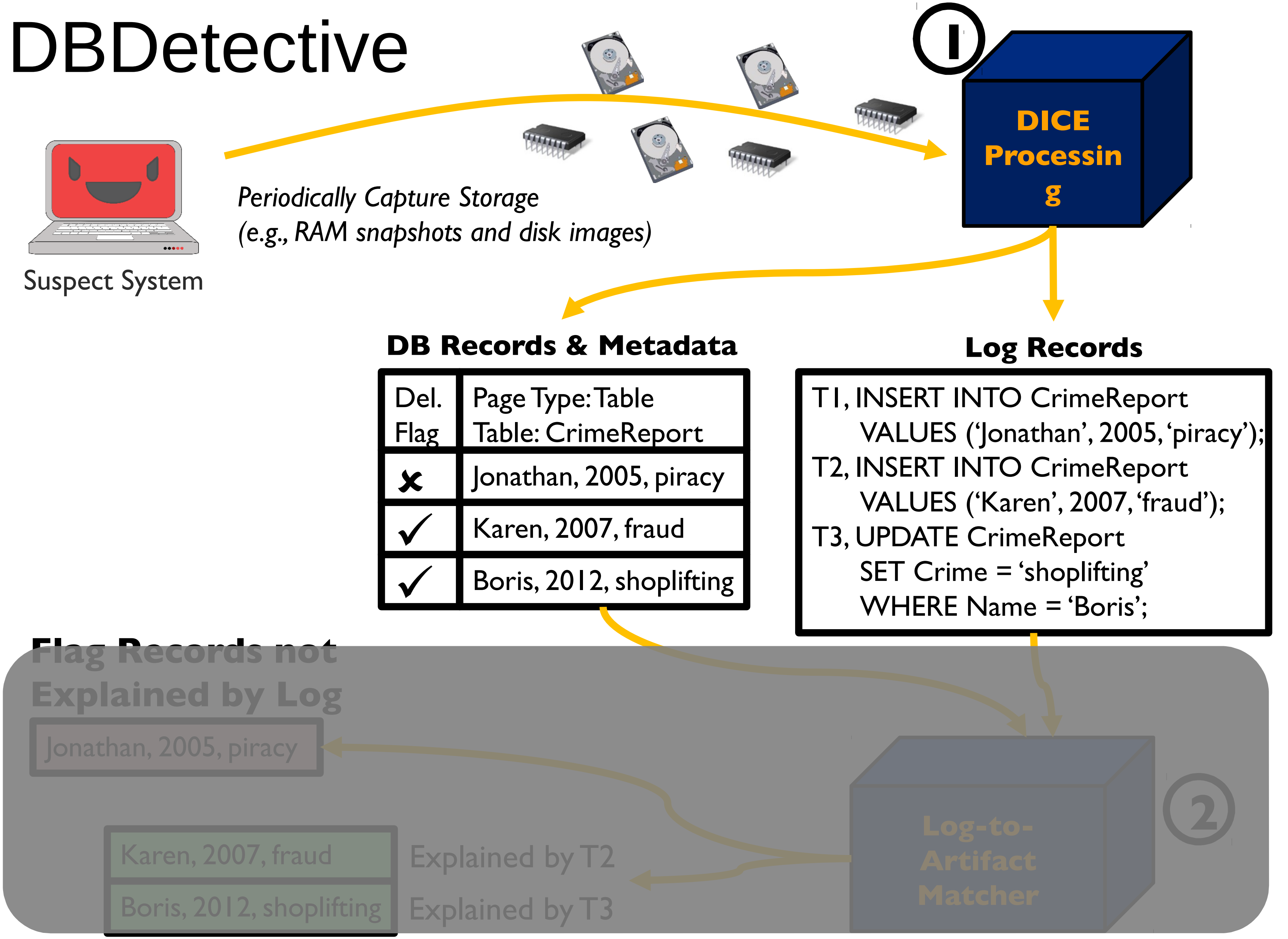
Flag Records not Explained by Log

Jonathan, 2005, piracy

Karen, 2007, fraud — Explained by T2

Boris, 2012, shoplifting — Explained by T3

DBDetective



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Flag Records not Explained by Log

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Boris, 2012, shoplifting — Explained by T3

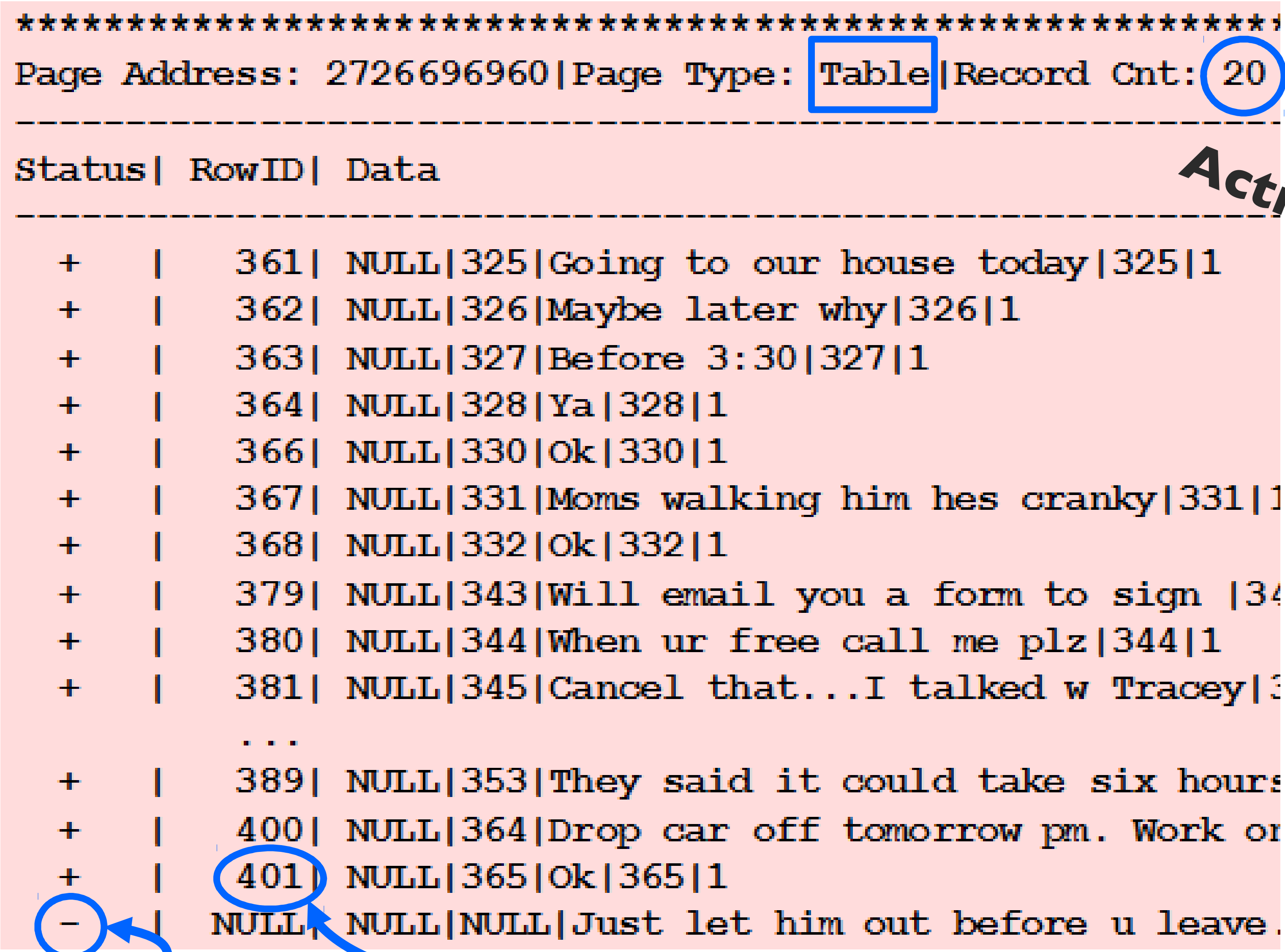
Database Image Content Explorer: DICE

- Implementation of **database page carving**

- Database page carving:
  - a solution to file carving for database files
  - reconstructs the database at the page level
  - returns records, indexes, metadata, and other artifacts
  - database files, disk images, or RAM snapshots

- Previously presented at DFRWS USA 2015 & 2016:
  - J. Wagner, A. Rasin, J. Grier, Database Forensic Analysis through Internal Structure Carving
  - J. Wagner, A. Rasin, J. Grier, Database Image Content Explorer: Carving Data that does not Officially Exist

DICE Example: Android Phone Data



```
*******************************************************
Page Address: 2726696960|Page Type: Table|Record Cnt: 20
-------------------------------------------------------
Status| RowID| Data
-------------------------------------------------------
  +   |   361| NULL|325|Going to our house today|325|1
  +   |   362| NULL|326|Maybe later why|326|1
  +   |   363| NULL|327|Before 3:30|327|1
  +   |   364| NULL|328|Ya|328|1
  +   |   366| NULL|330|Ok|330|1
  +   |   367| NULL|331|Moms walking him hes cranky|331|1
  +   |   368| NULL|332|Ok|332|1
  +   |   379| NULL|343|Will email you a form to sign |34
  +   |   380| NULL|344|When ur free call me plz|344|1
  +   |   381| NULL|345|Cancel that...I talked w Tracey|3
             ...
  +   |   389| NULL|353|They said it could take six hours
  +   |   400| NULL|364|Drop car off tomorrow pm. Work on
  +   |   401| NULL|365|Ok|365|1
  -   |  NULL| NULL|NULL|Just let him out before u leave.
```

Active Rows

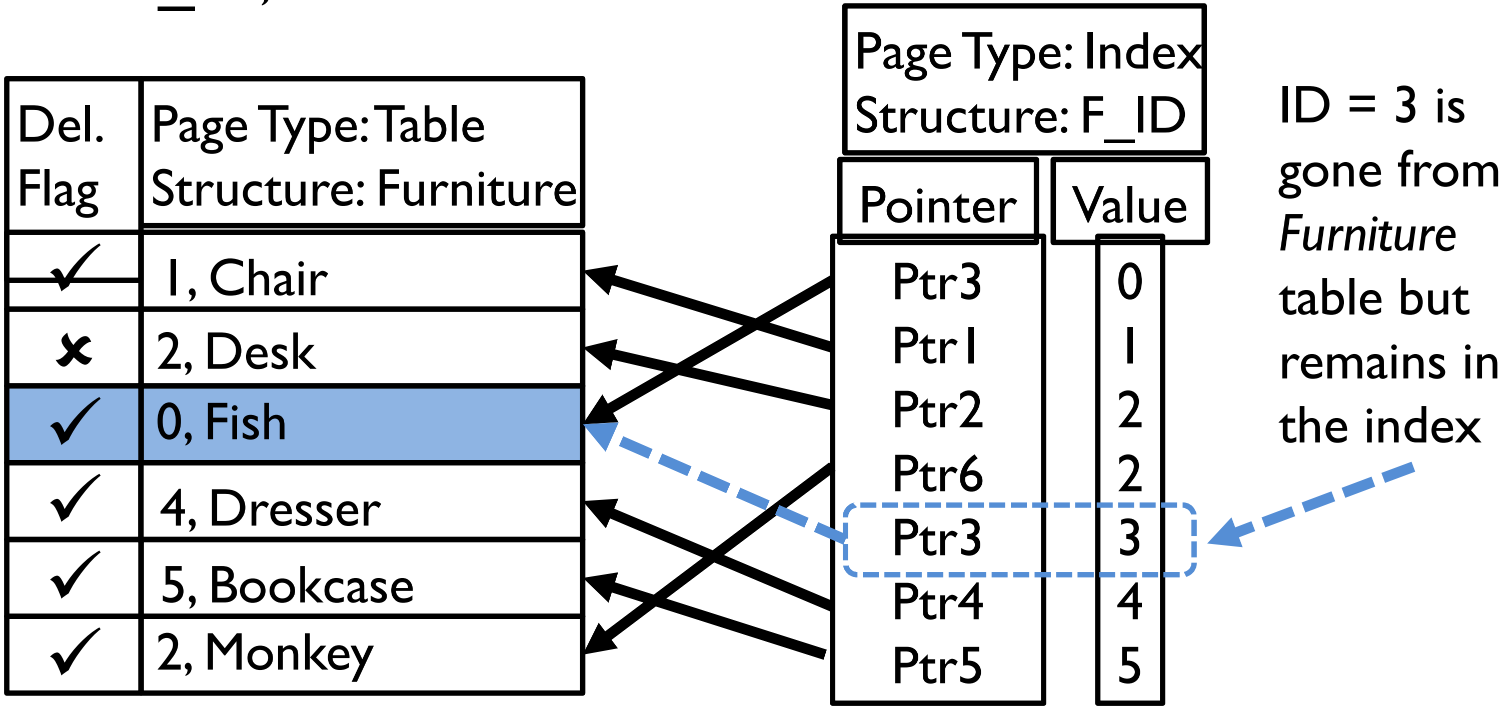
Deleted Row

Internal RowID (not part of user data)

DICE Example: Carving Indexes

- Indexes store value-pointer pairs used to read specific table pages
- Deleted index values often have a longer lifetime than deleted table records.
- Indexes can’t be directly queried. Ex.

✗
```
SELECT *
FROM F_ID;
```



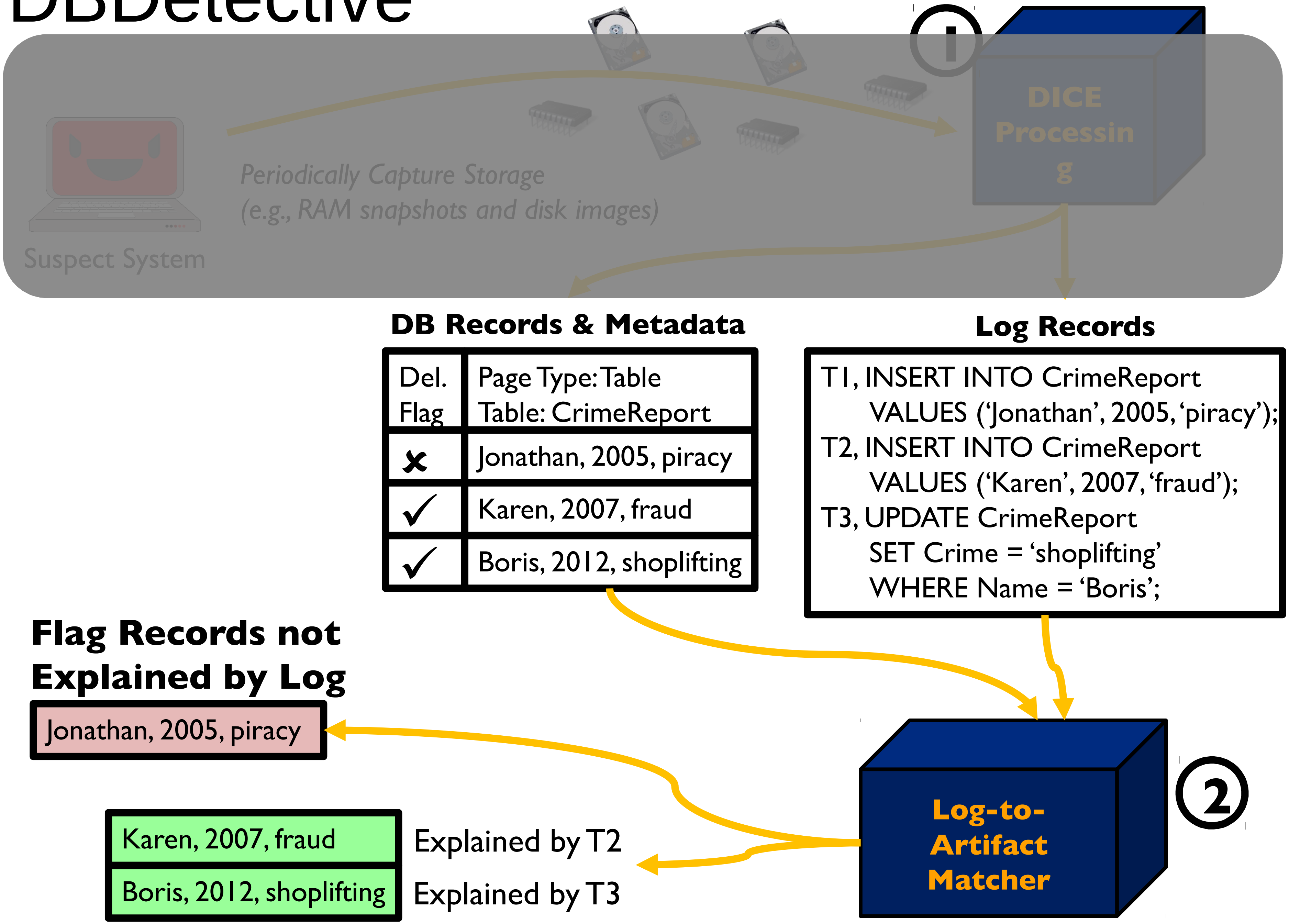
Del. Flag	Page Type: Table Structure: Furniture
✓	1, Chair
✗	2, Desk
✓	0, Fish
✓	4, Dresser
✓	5, Bookcase
✓	2, Monkey

Page Type: Index
Structure: F_ID

Pointer	Value
Ptr3	0
Ptr1	1
Ptr2	2
Ptr6	2
Ptr3	3
Ptr4	4
Ptr5	5

ID = 3 is gone from *Furniture* table but remains in the index

DBDetective



Suspect System

Periodically Capture Storage
(e.g., RAM snapshots and disk images)

① DICE Processin g

DB Records & Metadata

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Log Records

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      SET Crime = 'shoplifting'
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```

② **Log-to-Artifact Matcher**

Flag Records not Explained by Log

Jonathan, 2005, piracy

Karen, 2007, fraud	Explained by T2
Boris, 2012, shoplifting	Explained by T3

Log-to-Artifact Matcher

- Evaluate the integrity of carved data and metadata using log entries.

Data modifications (disk images):

1. DELETE

2. INSERT

3. UPDATE

★ **D**ata **D**efinition **L**anguage (e.g., CREATE, ALTER, DROP)

Read-only queries (RAM snapshots):

4. SELECT

★ Read only queries do not leave evidence on disk

Deleted Record-to-Log Matching

- Only the deleted records from the DICE output need to be considered.
- Only the DELETE commands from the log are considered.

DICE Output

Del. Flag	Page Type: Table Structure: Customer
✗	1, Christine, Chicago
✓	2, George, New York
✗	3, Christopher, Seattle
✗	4, Thomas, Austin
✓	5, Mary, Boston

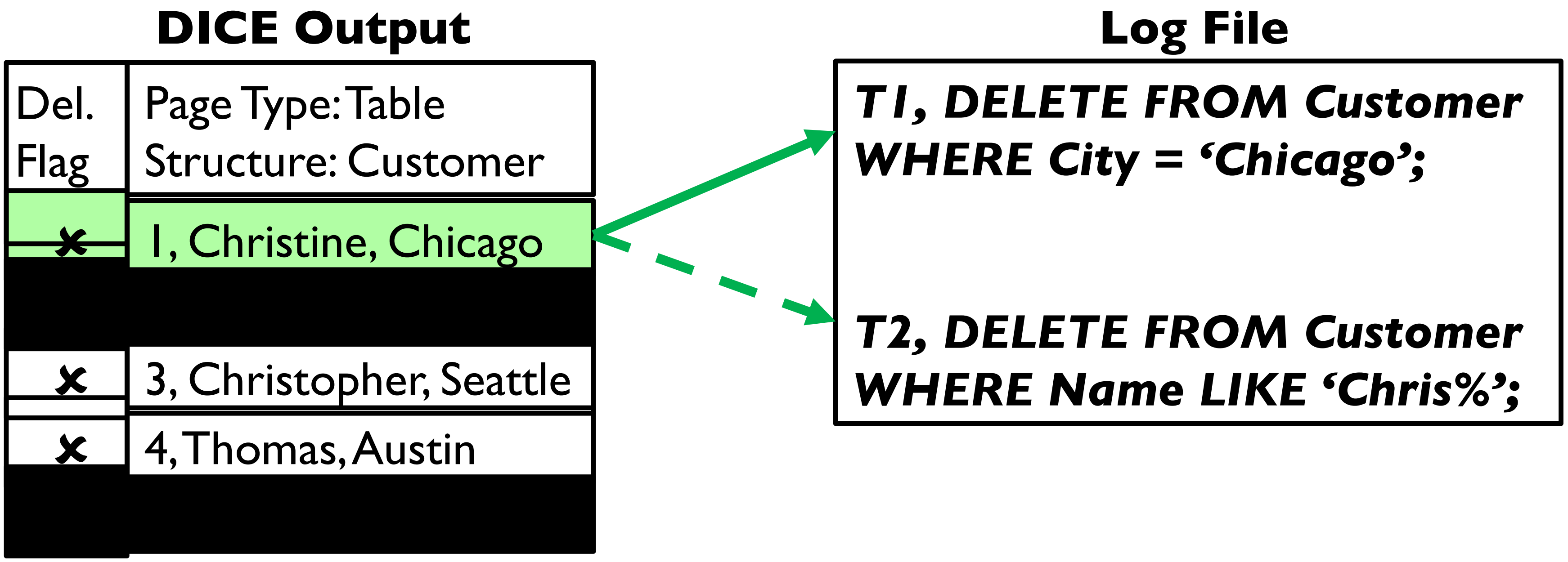
Log File

T1, DELETE FROM Customer WHERE City = ‘Chicago’;

T2, DELETE FROM Customer WHERE Name LIKE ‘Chris%’;

Deleted Record-to-Log Matching

- Any command that explains a record is considered, not the specific command.
- Name LIKE ‘Chris%’ vs City = ‘Chicago’ ➡ (1, Christine, Chicago)



DICE Output

Del. Flag	Page Type: Table Structure: Customer
✗	1, Christine, Chicago
[redacted]	[redacted]
✗	3, Christopher, Seattle
✗	4, Thomas, Austin
[redacted]	[redacted]

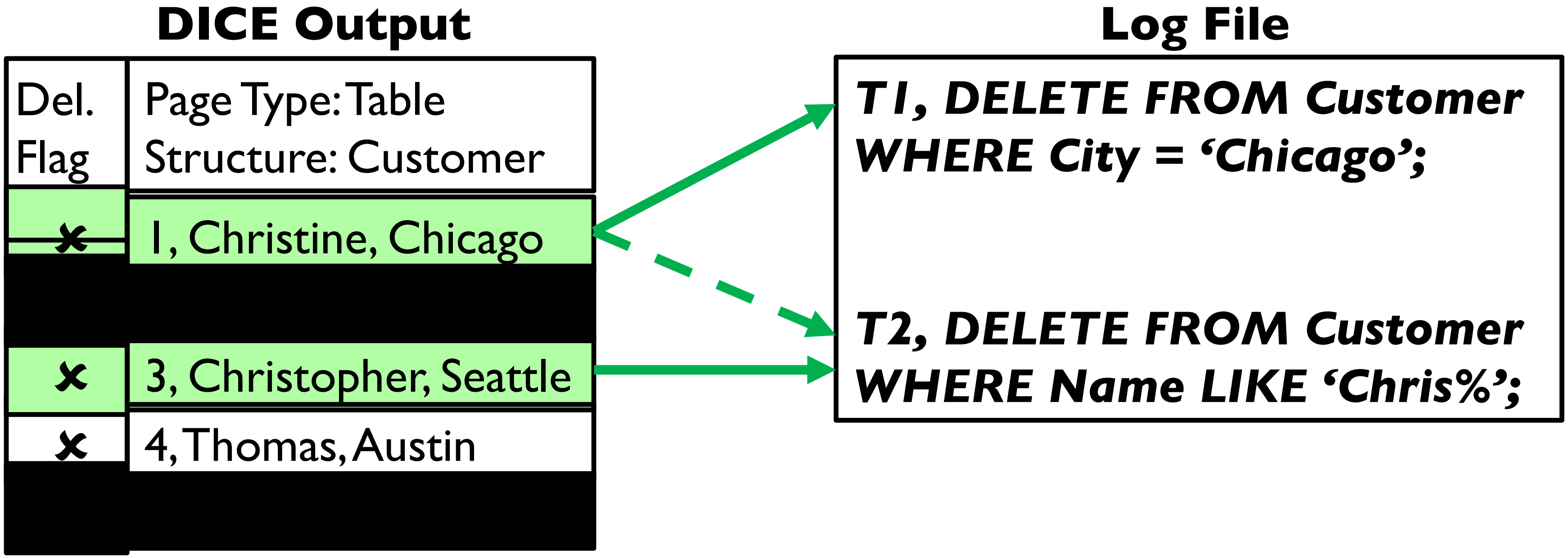
Log File

T1, DELETE FROM Customer WHERE City = ‘Chicago’;

T2, DELETE FROM Customer WHERE Name LIKE ‘Chris%’;

Deleted Record-to-Log Matching

- Name LIKE 'Chris%' explains the deleted record (3, Christopher, Seattle)



DICE Output

Del. Flag	Page Type: Table Structure: Customer
✗	1, Christine, Chicago
[redacted]	[redacted]
✗	3, Christopher, Seattle
✗	4, Thomas, Austin
[redacted]	[redacted]

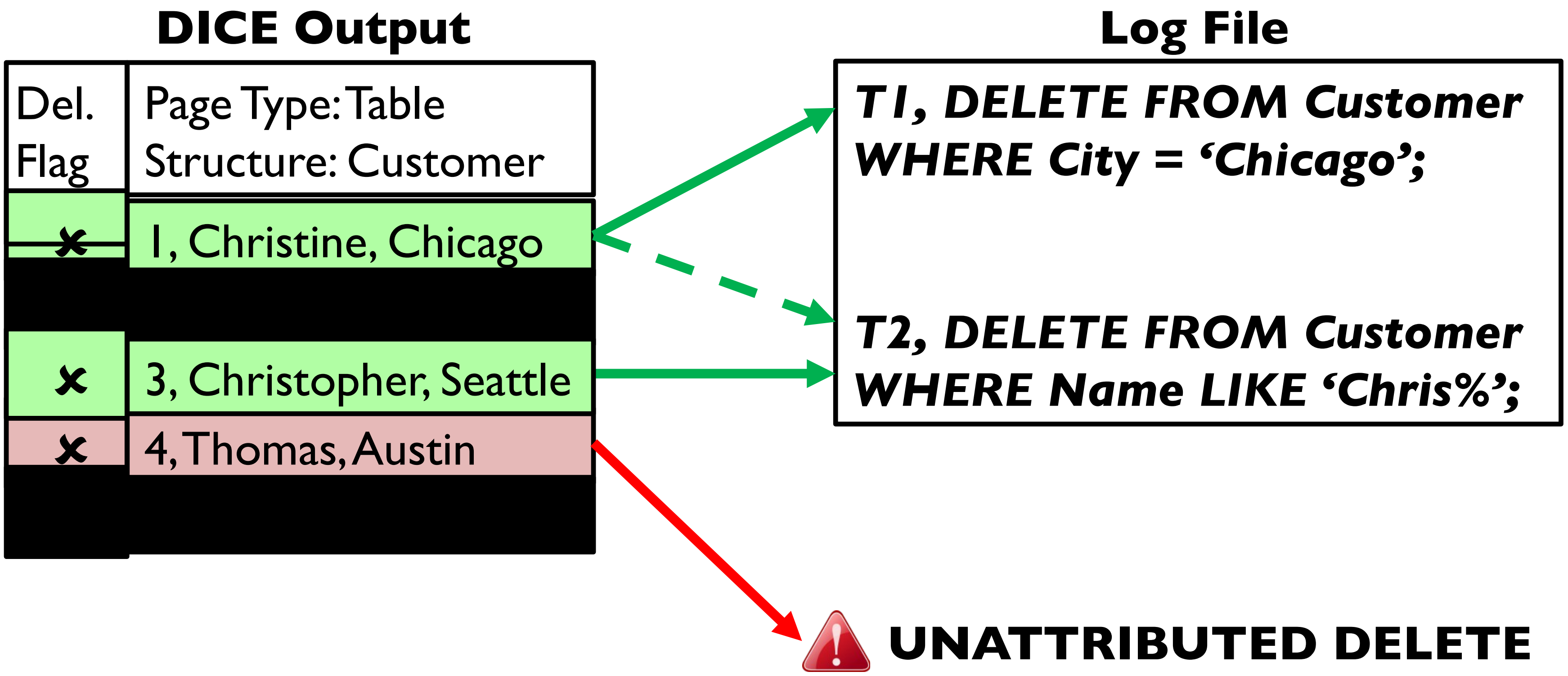
Log File

T1, DELETE FROM Customer WHERE City = 'Chicago';

T2, DELETE FROM Customer WHERE Name LIKE 'Chris%';

Deleted Record-to-Log Matching

- None of the DELETE commands can explain the deleted record (4, Thomas, Austin)



DICE Output

Del. Flag	Page Type: Table Structure: Customer
✗	1, Christine, Chicago
[redacted]	[redacted]
✗	3, Christopher, Seattle
✗	4, Thomas, Austin
[redacted]	[redacted]

Log File

T1, DELETE FROM Customer WHERE City = 'Chicago';

T2, DELETE FROM Customer WHERE Name LIKE 'Chris%';

UNATTRIBUTED DELETE

Log-to-Artifact Matcher

- Evaluate the integrity of carved data and metadata using log entries.

Data modifications (disk images):

1. DELETE
2. **INSERT**
3. UPDATE

★ **D**ata **D**efinition **L**anguage (e.g., CREATE, ALTER, DROP)

Read-only queries (RAM snapshots):

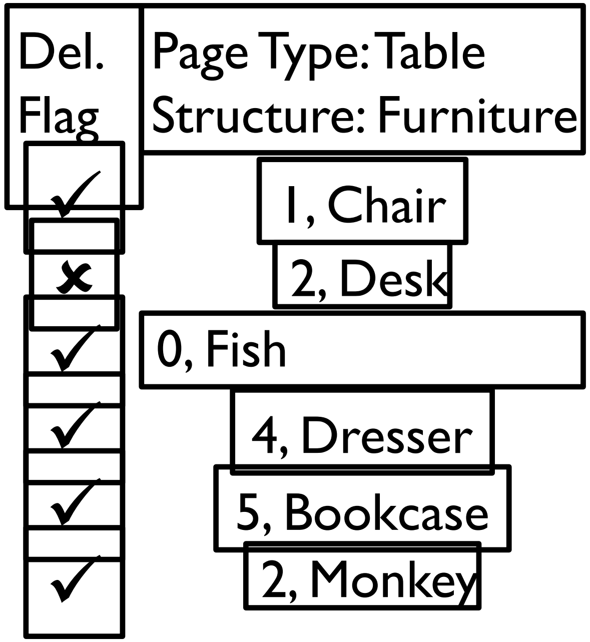
4. SELECT

★ Read only queries do not leave evidence on disk

Active Record-to-Log Matching

- Similar process as deleted record-to-log matching.

DICE Output



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✓	1, Chair
✗	2, Desk
✓	0, Fish
✓	4, Dresser
✓	5, Bookcase
✓	2, Monkey

Log File

T1, INSERT INTO Furniture
VALUES (1, ‘Chair’);

T2, INSERT INTO Furniture
VALUES (2, ‘Desk’);

T3, INSERT INTO Furniture
VALUES (3, ‘Lamp’);

T4, INSERT INTO Furniture
VALUES (4, ‘Dresser’);

T5, DELETE FROM Furniture
WHERE Name LIKE ‘Lamp’;

T6, INSERT INTO Furniture
VALUES (5,‘Bookcase’);

T7, UPDATE Furniture
SET Item = ‘Monkey’
WHERE ID = 2;

Active Record-to-Log Matching

- Only active records and INSERT commands are considered.

DICE Output

Del. Flag	Page Type: Table Structure: Furniture
✓	1, Chair
[redacted]	[redacted]
✓	0, Fish
✓	4, Dresser
✓	5, Bookcase
✓	2, Monkey

Log File

T1, INSERT INTO Furniture
VALUES (1, 'Chair');

T2, INSERT INTO Furniture
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T3, INSERT INTO Furniture
VALUES (3, 'Lamp');

T4, INSERT INTO Furniture
VALUES (4, 'Dresser');

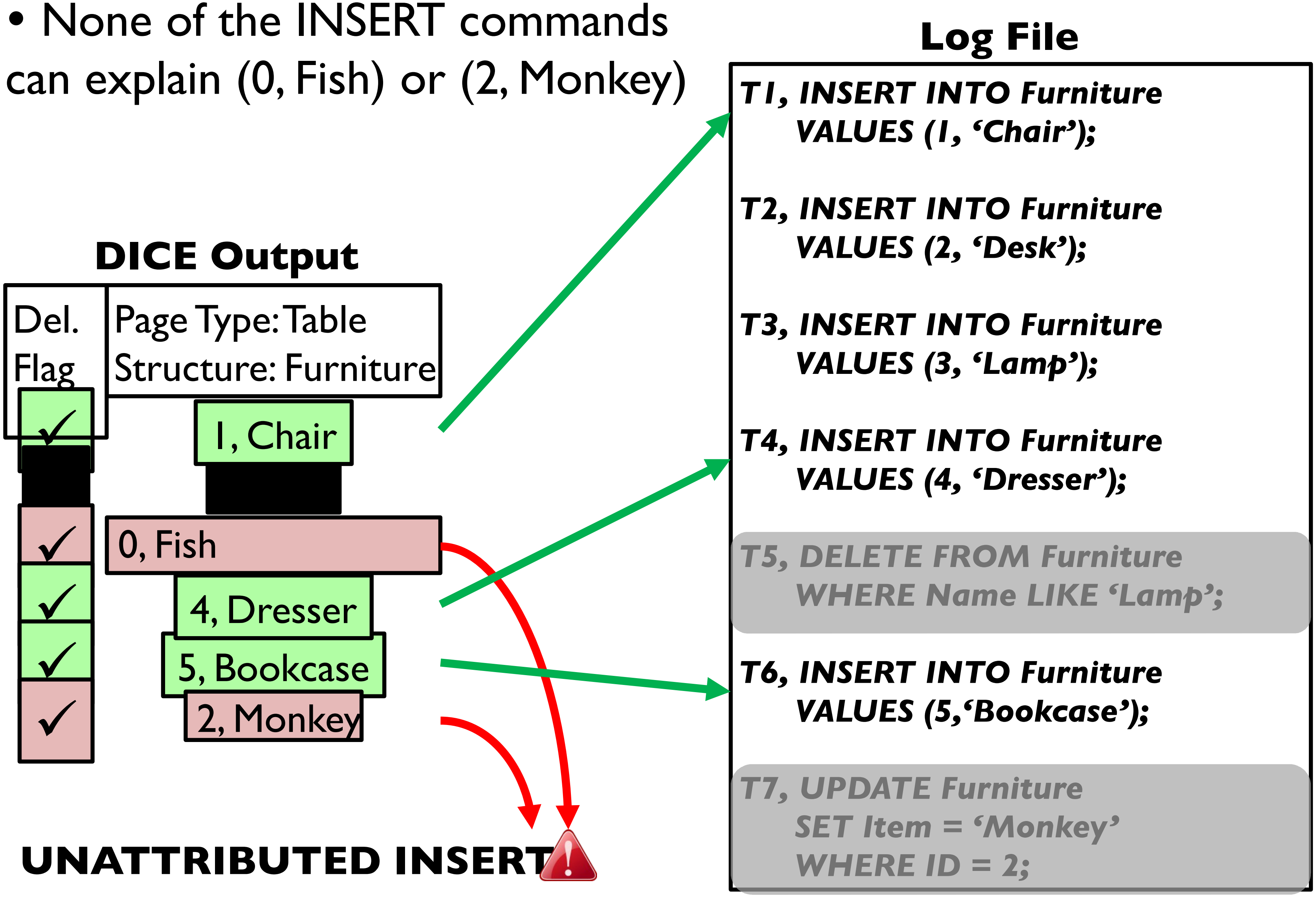
T5, DELETE FROM Furniture
WHERE Name LIKE 'Lamp';

T6, INSERT INTO Furniture
VALUES (5,'Bookcase');

T7, UPDATE Furniture
SET Item = 'Monkey'
WHERE ID = 2;

Active Record-to-Log Matching

- None of the INSERT commands can explain (0, Fish) or (2, Monkey)



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✓	1, Chair
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✓	5, Bookcase
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```

UNATTRIBUTED INSERT

Log-to-Artifact Matcher

- Evaluate the integrity of carved data and metadata using log entries.

Data modifications (disk images):

1. DELETE
2. INSERT
3. **UPDATE**

★ **D**ata **D**efinition **L**anguage (e.g., CREATE, ALTER, DROP)

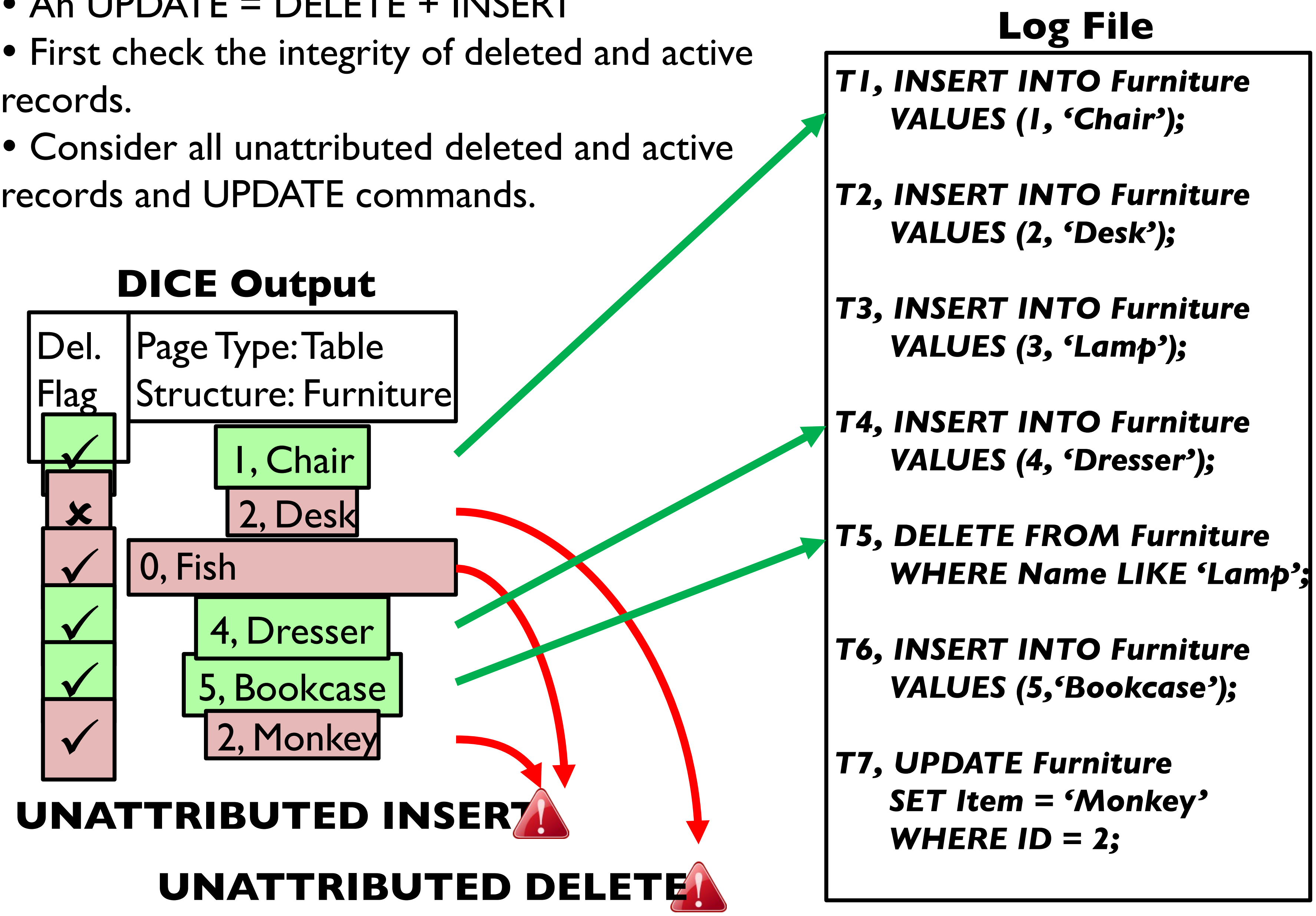
Read-only queries (RAM snapshots):

4. SELECT

★ Read only queries do not leave evidence on disk

Updated Record-to-Log Matching

- An UPDATE = DELETE + INSERT
- First check the integrity of deleted and active records.
- Consider all unattributed deleted and active records and UPDATE commands.



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UNATTRIBUTED INSERT

UNATTRIBUTED DELETE

Log File

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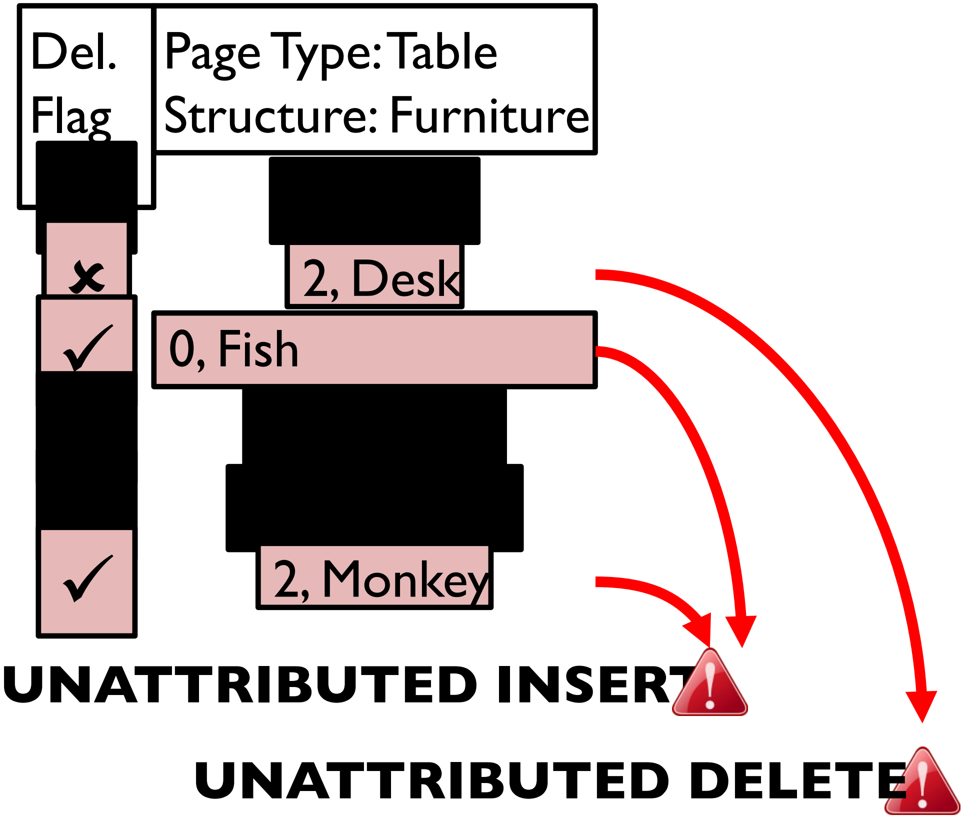
    VALUES (5,'Bookcase');

T7, UPDATE Furniture
    SET Item = 'Monkey'
    WHERE ID = 2;
```

Updated Record-to-Log Matching

- Consider all unattributed deleted and active records and UPDATE commands.
  - deleted record ➡ WHERE clause
  - active records ➡ SET clause

DICE Output



Del. Flag	Page Type: Table Structure: Furniture
[redacted]	[redacted]
✗	2, Desk
✓	0, Fish
[redacted]	[redacted]
[redacted]	[redacted]
✓	2, Monkey

UNATTRIBUTED INSERT

UNATTRIBUTED DELETE

Log File

```
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    VALUES (1, 'Chair');
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    VALUES (3, 'Lamp');
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    VALUES (4, 'Dresser');
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    WHERE Name LIKE 'Lamp';
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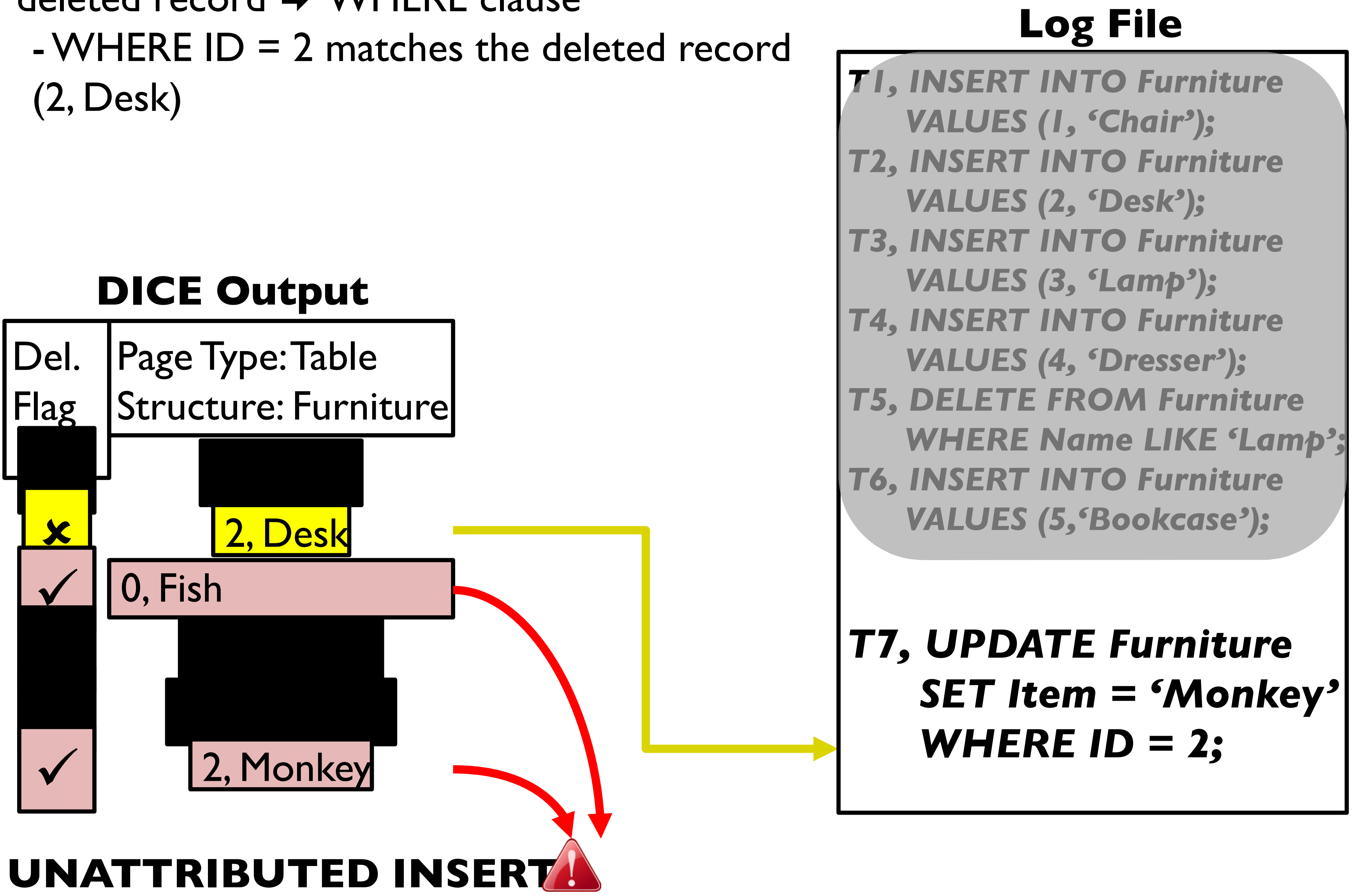
    VALUES (5,'Bookcase');

T7, UPDATE Furniture
     SET Item = 'Monkey'
     WHERE ID = 2;
```

Updated Record-to-Log Matching

- deleted record ➡ WHERE clause
  - WHERE ID = 2 matches the deleted record (2, Desk)



DICE Output

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UNATTRIBUTED INSERT

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VALUES (5,'Bookcase');

T7, UPDATE Furniture
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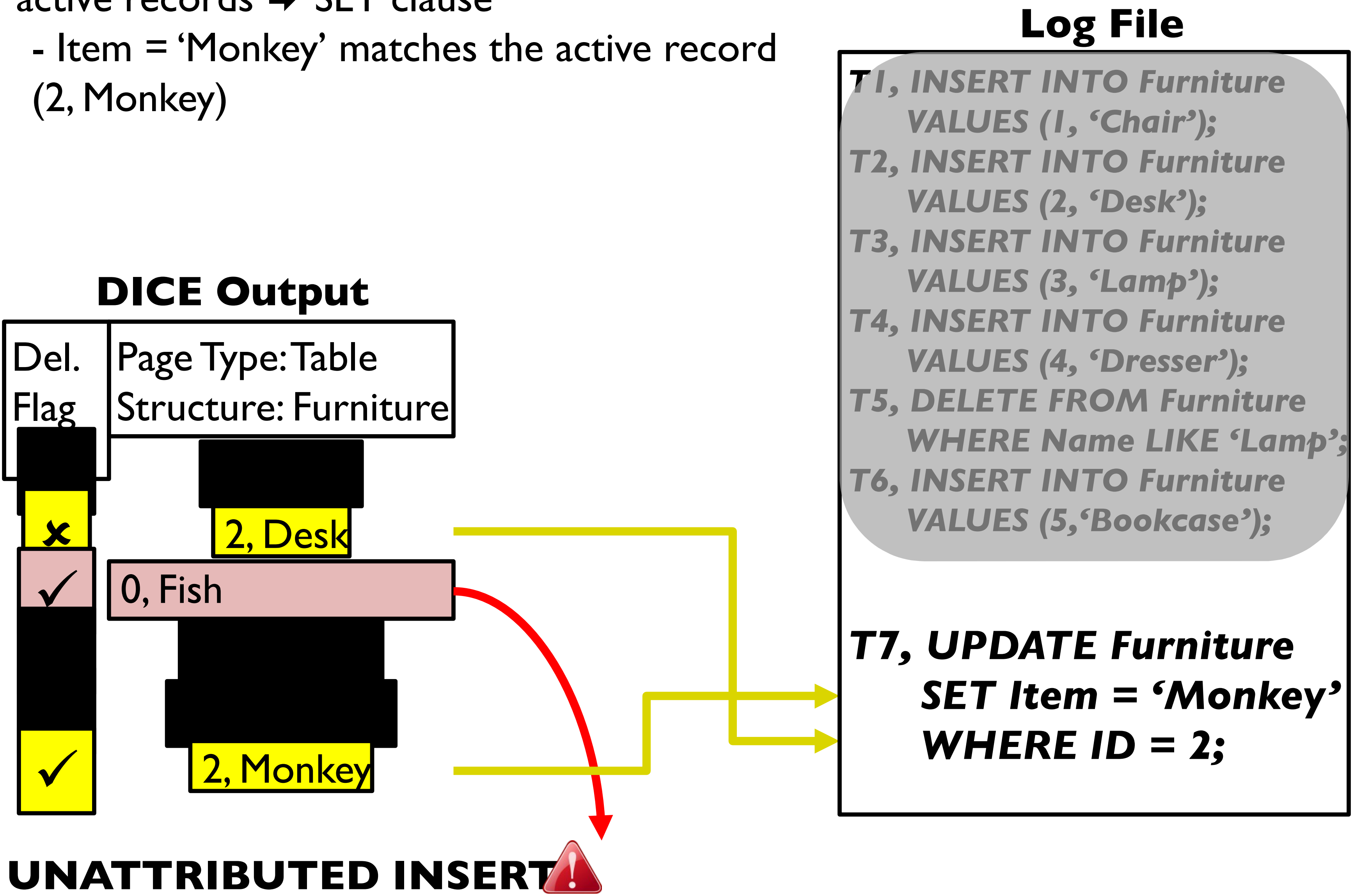
WHERE ID = 2;

Updated Record-to-Log Matching

- active records ➡ SET clause
  - Item = ‘Monkey’ matches the active record (2, Monkey)



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UNATTRIBUTED INSERT

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T7, UPDATE Furniture
    SET Item = ‘Monkey’
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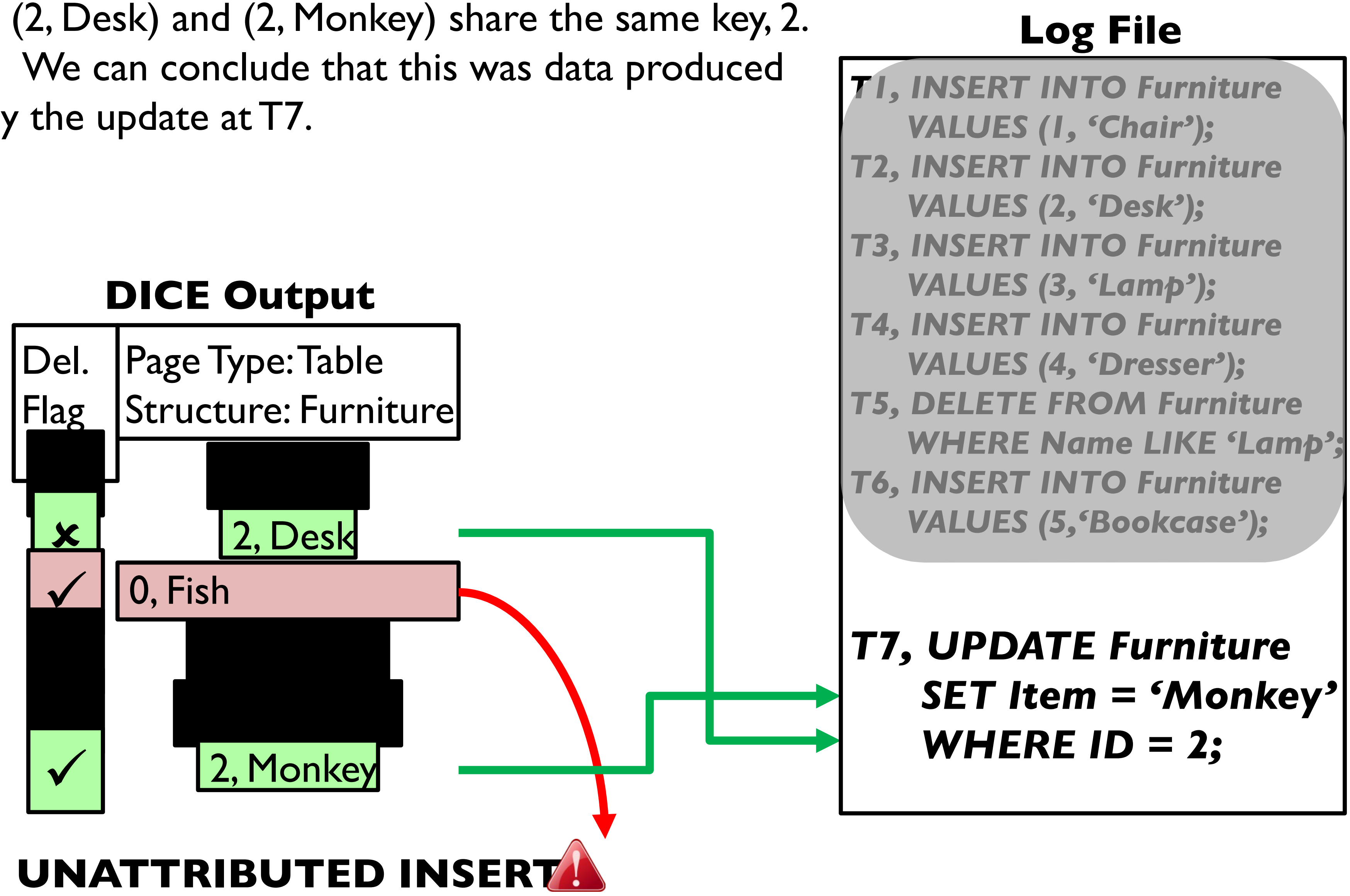
```

Updated Record-to-Log Matching

- (2, Desk) and (2, Monkey) share the same key, 2.
- We can conclude that this was data produced by the update at T7.



Log File

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SET Item = 'Monkey'
WHERE ID = 2;

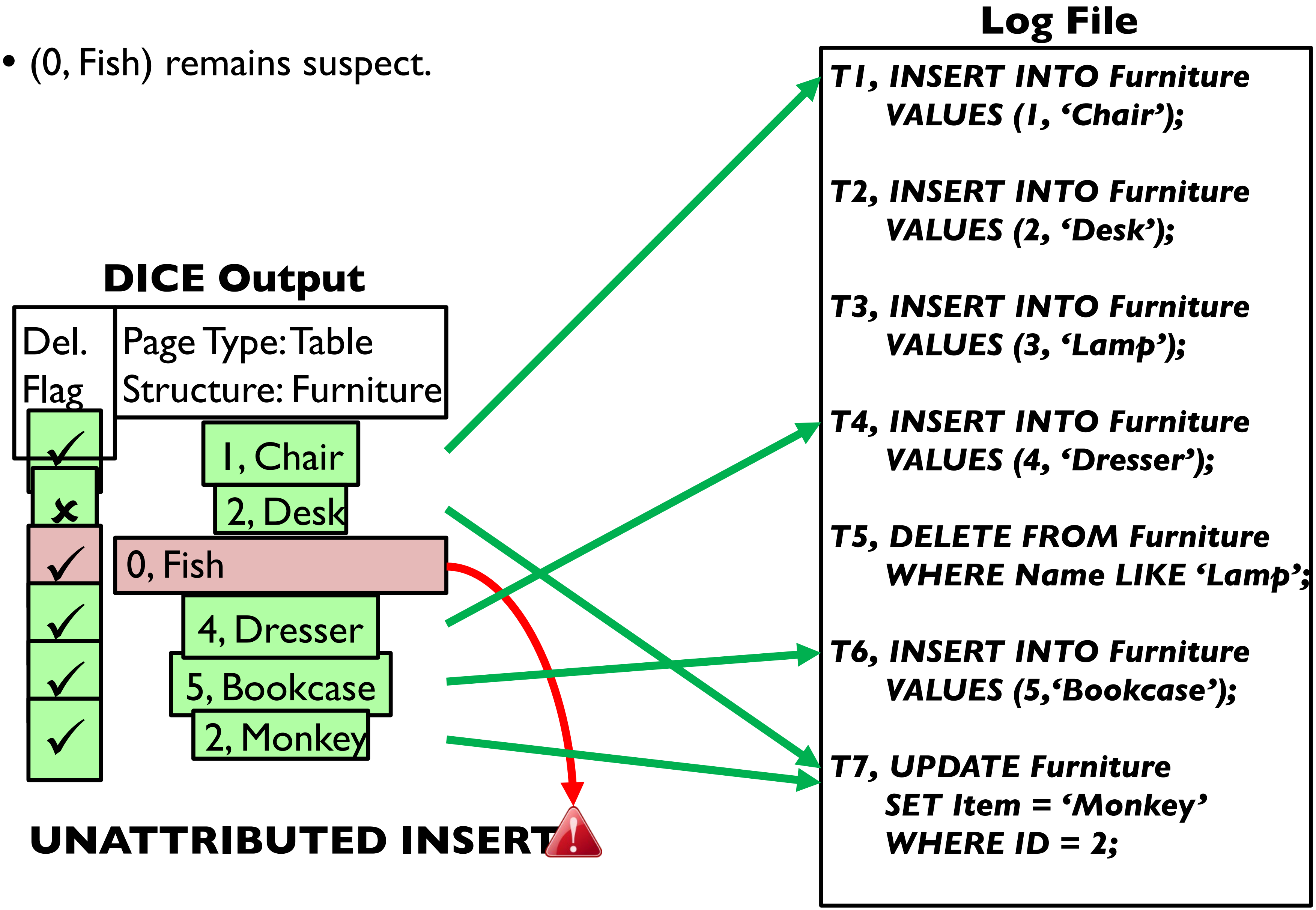
DICE Output

Del. Flag	Page Type: Table Structure: Furniture
✗	2, Desk
✓	0, Fish
✓	2, Monkey

UNATTRIBUTED INSERT

Updated Record-to-Log Matching

- (0, Fish) remains suspect.



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Log-to-Artifact Matcher

- Evaluate the integrity of carved data and metadata using log entries.

Data modifications (disk images):

1. DELETE
2. INSERT
3. UPDATE

★ **D**ata **D**efinition **L**anguage (e.g., CREATE, ALTER, DROP)

Read-only queries (RAM snapshots):

4. SELECT

★ Read only queries do not leave evidence on disk

Select Query-to-Log Matching

- All SELECT queries use either a:
  1. Full table scan (FTS)
  2. Index access.

  ★ Views ultimately access tables and materialized views behave

  similar to tables.

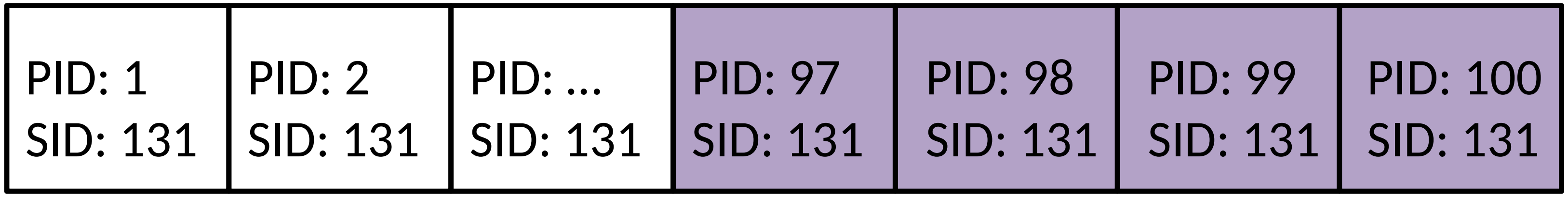
FTS

- the entire table is scanned
- the DBMS allocates a limited amount of memory
- the end result of a FTS is the last N pages of the table from the database file (i.e., a repeating pattern)

Full Table Scan: Example

- Table Employee has 100 pages.
- The DBMS allocates 4 pages to a FTS.
- A FTS of Employee leaves pages 97, 98, 99, and 100 in RAM.

Table Employee on Disk



PID: 1 SID: 131

PID: 2 SID: 131

PID: … SID: 131

PID: 97 SID: 131

PID: 98 SID: 131

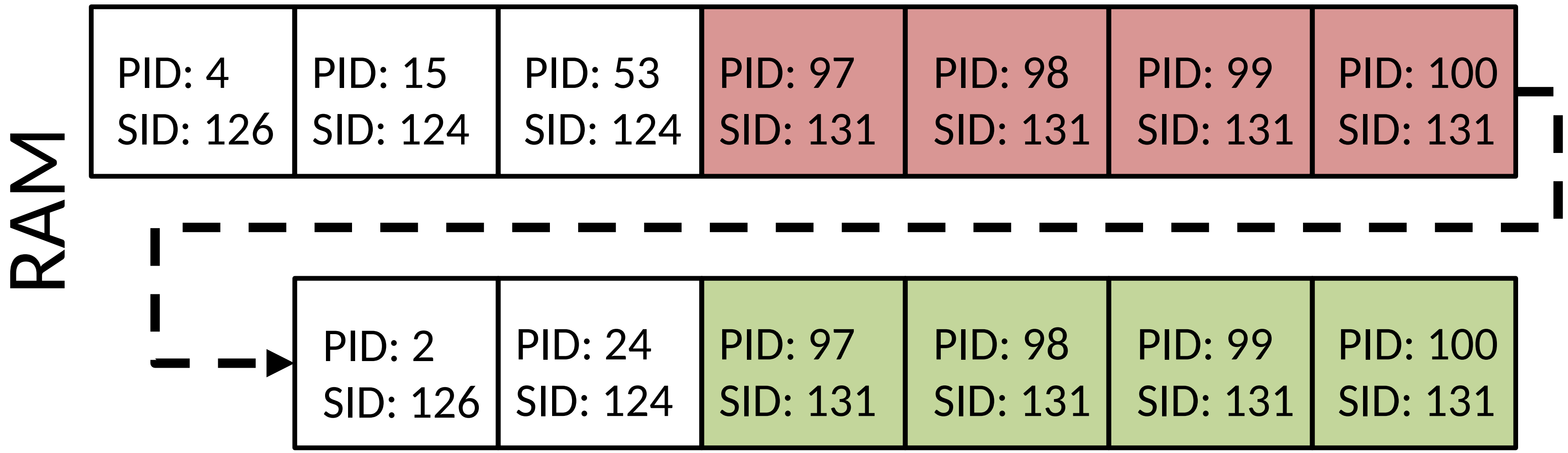
PID: 99 SID: 131

PID: 100 SID: 131

▨ Full table scan result in buffer cache

PID: Page ID
SID: Structure ID

Full Table Scans



RAM

PID: 4 SID: 126 | PID: 15 SID: 124 | PID: 53 SID: 124 | PID: 97 SID: 131 | PID: 98 SID: 131 | PID: 99 SID: 131 | PID: 100 SID: 131

PID: 2 SID: 126 | PID: 24 SID: 124 | PID: 97 SID: 131 | PID: 98 SID: 131 | PID: 99 SID: 131 | PID: 100 SID: 131

Audit Log

```
T1, SELECT C_Name
FROM Customer
WHERE C_City = ‘Jackson’;

T2, SELECT E_Name, E_Salary
FROM Employee;

T3, SELECT *
FROM Customer
WHERE C_City = ‘Dallas’;

T4, SELECT *
FROM Employee
WHERE E_Name LIKE ‘%ne’;
```

Select Query-to-Log Matching

- All SELECT queries use either a:
  1. Full table scan (FTS)
  2. Index access

  ★ Views ultimately access tables and materialized views behave similar to tables.

Index Access

- an index stores value-pointer pairs to access specific table pages
- both the index pages and table pages are cached
- table pages may contain data unrelated to query
- index pages contain ordered values giving us a range of possible filters

Index Access: Example 1

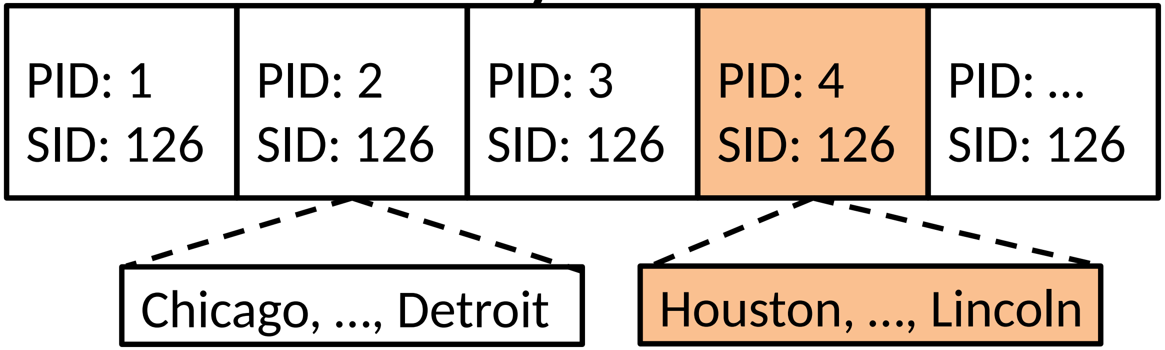
Query I

SELECT C_Name
FROM Customer
WHERE C_City = ‘Jackson’;

- Query I filters on City = ‘Jackson’
- Page ID = 4 gets read into RAM
- The relevant table pages are read into RAM

PID: Page ID
SID: Structure ID

Index Customer City on Disk



Index Access: Example 2

Query 2

SELECT *

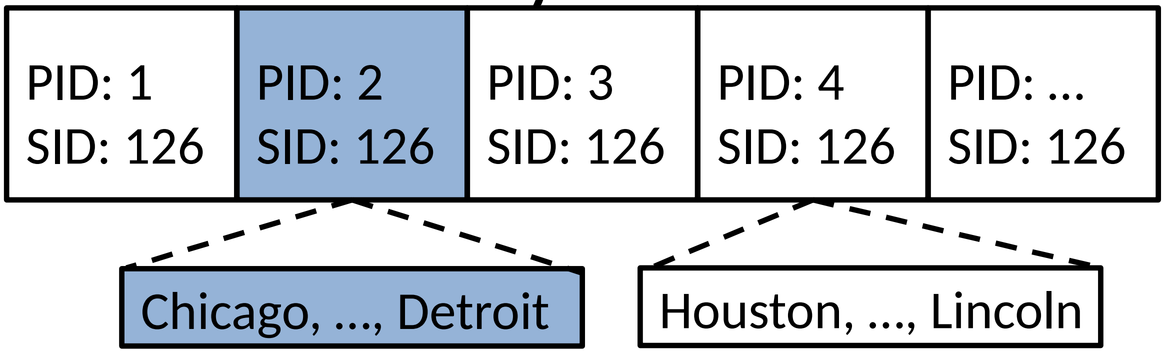
FROM Customer

WHERE C_City = ‘Dallas’;

- Query filters on City = ‘Dallas’
- Page ID = 2 gets read into RAM
- The relevant table pages are read into RAM

PID: Page ID
SID: Structure ID

Index Customer City on Disk



PID: 1
SID: 126

PID: 2
SID: 126

PID: 3
SID: 126

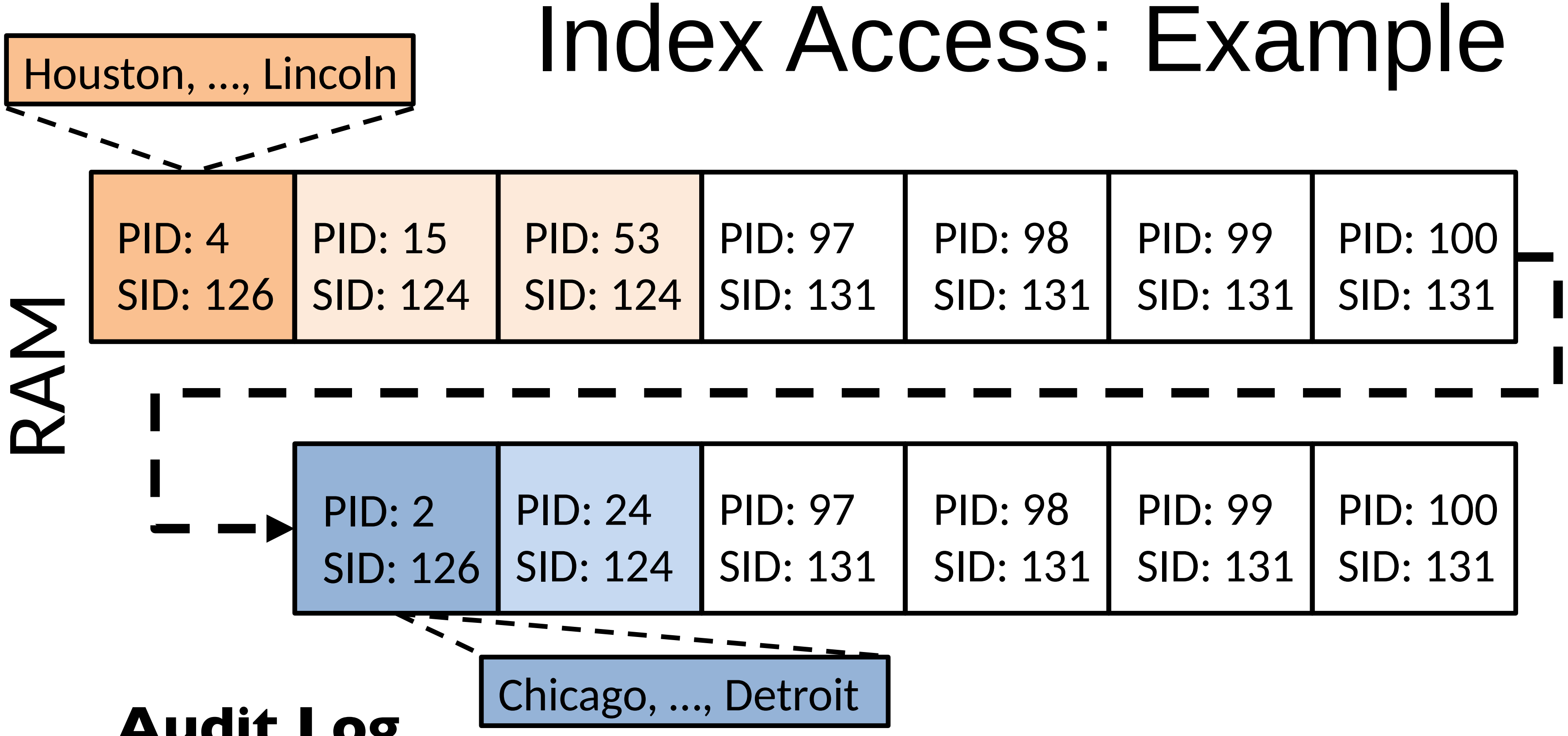
PID: 4
SID: 126

PID: …
SID: 126

Chicago, …, Detroit

Houston, …, Lincoln

Index Access: Example



PID: 4 SID: 126	PID: 15 SID: 124	PID: 53 SID: 124	PID: 97 SID: 131	PID: 98 SID: 131	PID: 99 SID: 131	PID: 100 SID: 131

PID: 2 SID: 126	PID: 24 SID: 124	PID: 97 SID: 131	PID: 98 SID: 131	PID: 99 SID: 131	PID: 100 SID: 131

Audit Log

T1, SELECT C_Name
FROM Customer
WHERE C_City = ‘Jackson’;

T2, SELECT E_Name, E_Salary
FROM Employee;

T3, SELECT *
FROM Customer
WHERE C_City = ‘Dallas’;

T4, SELECT *
FROM Employee
WHERE E_Name LIKE ‘%ne’;

Performance

DICE Processing

- DICE carves ~ 1.1 MB/s.
  - Several files from 1MB to 3 GB were tested.
- Carving is dependent on the # of pages, not file size:
  - 2.5 GB process snapshot with 600 MB of pages ➡ 4.2 MB/s
  - 8 GB RAM snapshot with 600 MB of pages ➡ 13.2 MB/s

Log-to-Artifact Matching

- Assuming the log can fit into memory, the cost is linear.
- DBDetective operates independent of the DBMS
- Carving and log-to-artifact matching can occur offsite

*checksum evaluation limits page parsing and artifact matching

Future Work

Timeline of Events

- Match data and metadata to specific commands in the log.
- Ex. Name LIKE ‘Chris%’ vs City = ‘Chicago’ ➡ (1, Christine, Chicago)

Detect Direct File Modifications

- Ex. ‘Karen’ was changed to ‘Boris’ in the database file using Python rather than SQL.
- Protect against other privileged users (system admin)
- All DBMS security (defense and detection) are bypassed

Questions?

Accuracy: False-Negatives

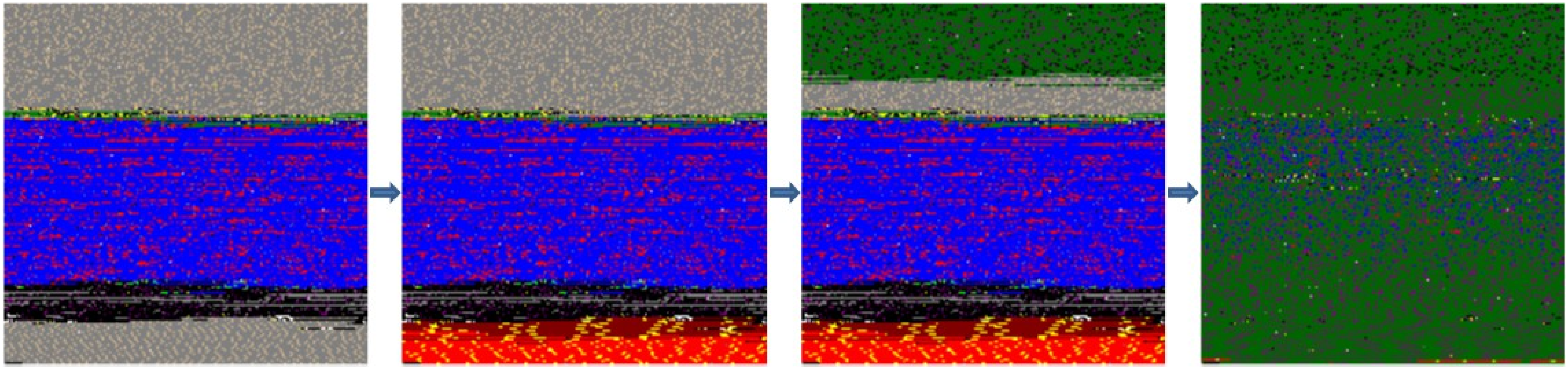
- The conditions for operations may overlap, creating false-negatives. Ex. Name LIKE ‘Chris%’ vs City = ‘Chicago’ ➡ (1, Christine, Chicago)

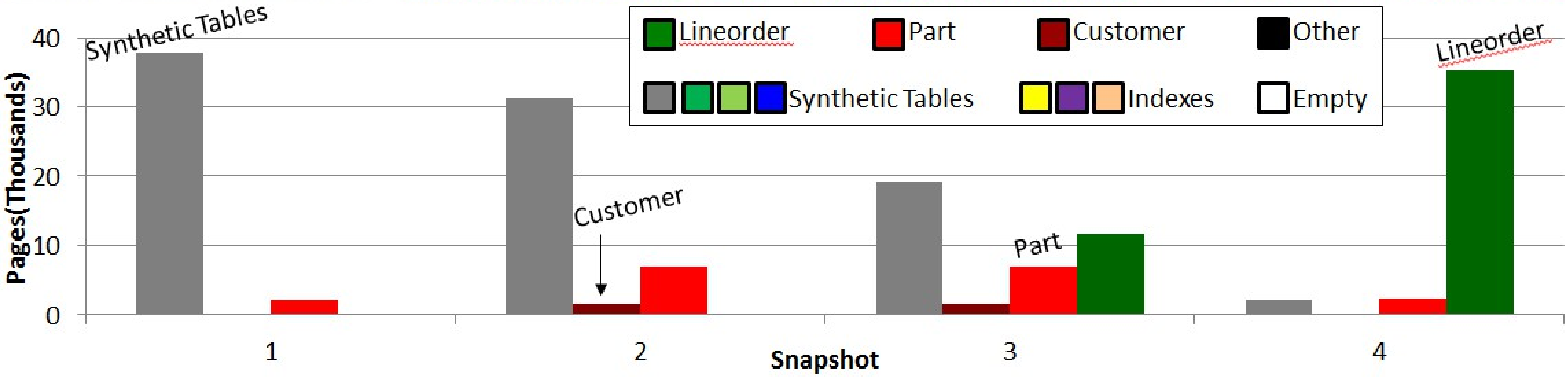
- We are interested in identifying data that does not match *any* log operation.

- False-negative present a problem if it the tampered data matches a pre-existing log operation. Ex.

  T1. DELETE FROM Customer WHERE Name LIKE ‘Chris%’;
  T2. DELETE FROM Customer WHERE City = ‘Chicago’;
  T3. INSERT INTO Customer VALUES (1, ‘Christine’, ‘Chicago’);
  T4. Logging is disabled and (1, Christine, Chicago) is deleted

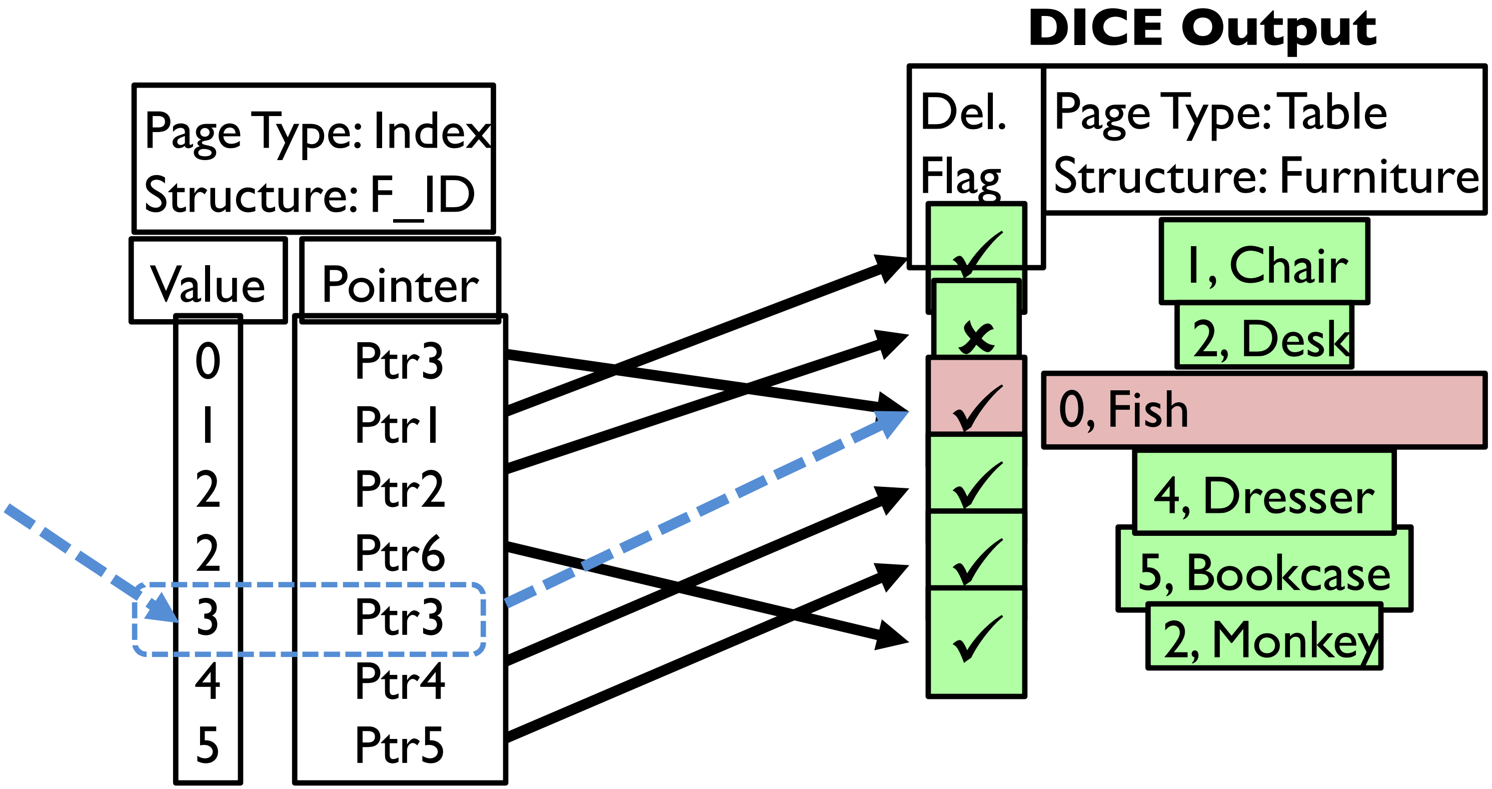
DICE Example: RAM Monitoring





Indexes

Value 3 is gone from *Furniture* table but remains in the index



DICE Output

Page Type: Index
Structure: F_ID

Value	Pointer
0	Ptr3
1	Ptr1
2	Ptr2
2	Ptr6
3	Ptr3
4	Ptr4
5	Ptr5

Del. Flag	Page Type: Table Structure: Furniture
✓	1, Chair
✗	2, Desk
✓	0, Fish
✓	4, Dresser
✓	5, Bookcase
✓	2, Monkey