

# Temporal Databases

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## What is a 'Temporal Database'

person			
name	salary	start_time	end_time
Peter	20000	1/1/1995	31/12/1997
Peter	22000	1/1/1998	15/4/1998
Peter	23000	16/4/1998	31/8/1998
Peter	25000	1/1/1999	31/10/2002
Mary	24000	1/1/1995	30/11/1998
Mary	26000	1/12/1998	15/3/2003

- Holds data with some temporal dimension
- Provides support for query processing over that data
  - *How do you find periods a person worked for the company?*

# Temporal Query Processing

```
SELECT name, start_time , end_time  
FROM person
```



person		
name	start_time	end_time
Peter	1/1/1995	31/12/1997
Peter	1/1/1998	15/4/1998
Peter	16/4/1998	31/8/1998
Peter	1/1/1999	31/10/2002
Mary	1/1/1995	30/11/1998
Mary	1/12/1998	15/3/2003

- *How do we merge periods?*

person		
name	start_time	end_time
Peter	1/1/1995	31/8/1998
Peter	1/1/1999	31/10/2002
Mary	1/1/1995	15/3/2003

## Two Types of Time to Store

### Temporal Dimensions

- **valid time** time data valid in UoD.  
e.g. *time payments and withdrawal movements made in branch*
- **transaction time** time data valid in the DBMS  
e.g. *from time the clerk entered the payment or withdrawal into the DBMS*
- Temporal database may store valid time, transaction time, or both
- Each type of time can be called a ‘flow of time’
- Same query language can be used on either ‘flow of time’
- Two dimensional query language required if both types stored in same database

## Modelling a flow of time

*There are several choices to make in modelling a flow of time*

### *Simple method*

#### **Discrete**

fixed **chronons**, have next and previous time

#### **Bounded**

first and last time

#### **Linear**

one view of each time

### *Complex method*

#### **Continuous**

always add a new time point between two other

#### **Unbounded**

all times may be represented

#### **Branching**

multiple views of each time

# Temporal Structure

<i>t</i>	time	account			movement			
	time	<u>no</u>	type	rate	<u>mid</u>	no	amount	
0	1/1/1999	100	'current'	NULL	0000	100	220.00	
		101	'deposit'	8.50	0001	102	2520.00	
		102	'deposit'	8.50				
1	2/1/1999	100	'current'	NULL	0002	101	100.00	
		101	'deposit'	8.25	0003	104	1000.00	
		103	'current'	NULL				
		104	'current'	NULL				
2	3/1/1999	100	'current'	NULL	0004	104	-500.00	
		101	'deposit'	8.25	0005	105	500.00	
		103	'current'	NULL	0006	100	100.23	
		104	'current'	NULL				
		105	'deposit'	8.50				

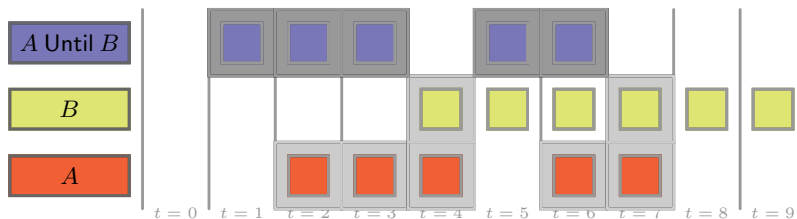
## Using RA on a Snapshot of the Temporal Structure

<i>t</i>	time	account			movement			
	time	<u>no</u>	type	rate	<u>mid</u>	no	amount	
1	2/1/1999	100	'current'	NULL	0002	101	100.00	
		101	'deposit'	8.25	0003	104	1000.00	
		103	'current'	NULL				
		104	'current'	NULL				

$eval(\pi_{no} \text{account}, 1)$
no
100
101
103
104

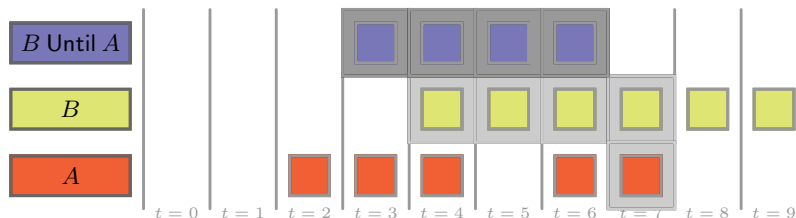
$eval(\pi_{no} \text{account} \times \pi_{mid} \text{movement}, 1)$			
no	mid	no	mid
100	0002	103	0002
101	0003	103	0003
103	0002	104	0002
104	0003	104	0003

## US-Logic: $A$ Until $B$



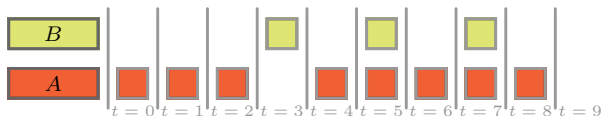
$A$  will hold at every time up to and including the time when  $B$  holds

# US-Logic: $B$ Until $A$



$B$  will hold at every time up to and including the time when  $A$  holds

## Quiz 1: Until modal logic operator



When does  $A$  Until  $B$  hold?

A



B



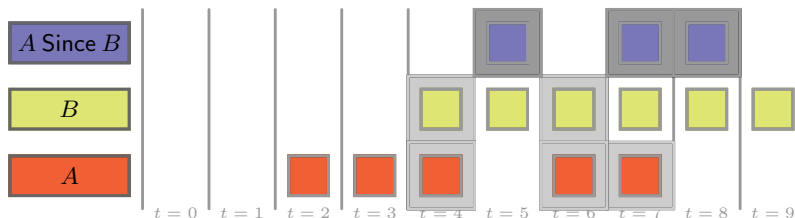
C



D

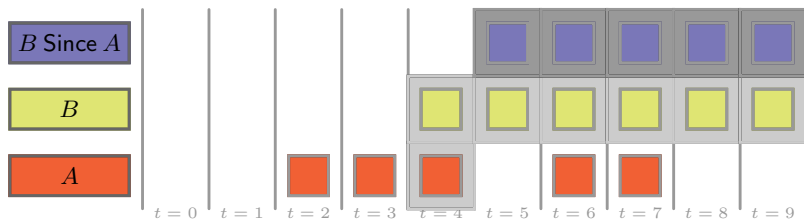


# US-Logic: $A$ Since $B$



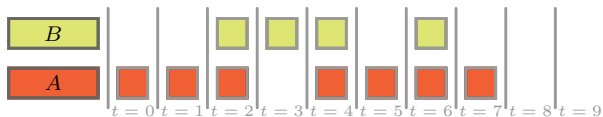
$A$  has held at every time since and including the time when  $B$  held

# US-Logic: $B$ Since $A$



$B$  has held at every time since and including the time when  $A$  held

## Quiz 2: Since modal logic operator



When does  $A$  Since  $B$  hold?

A



B



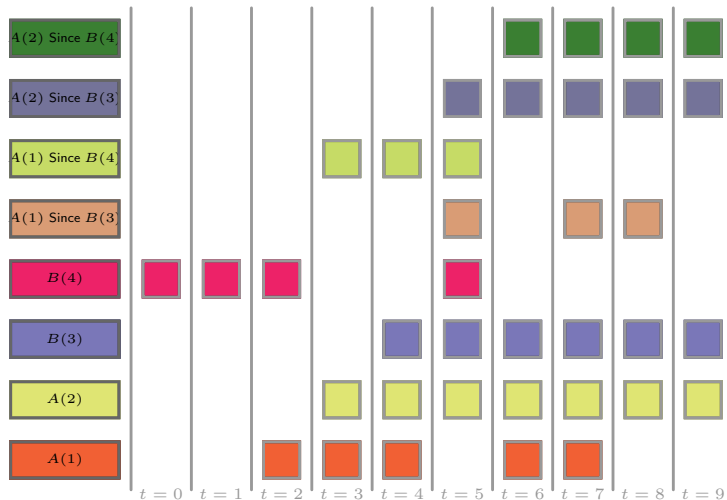
C



D



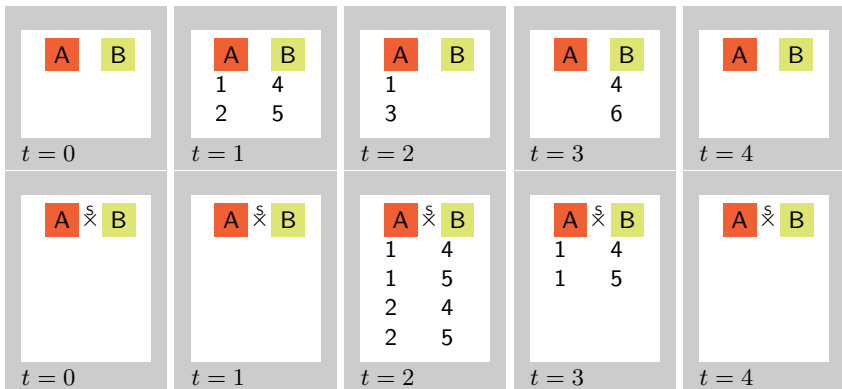
# Predicate US Logic



# Relational form of US Logic

## Since Product

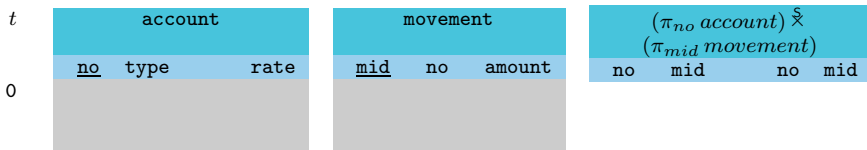
$$eval(R \overset{\times}{\bowtie} S, t) = eval((R \times S) \cup ((R \overset{\times}{\bowtie} S) \times R), t - 1)$$



## Until Product

$$eval(R \overset{\cup}{\bowtie} S, t) = eval((R \times S) \cup ((R \overset{\cup}{\bowtie} S) \times R), t + 1)$$

## Example of since-product



# Example of since-product

$t$	account			movement			$(\pi_{no} \text{ account}) \bowtie$ $(\pi_{mid} \text{ movement})$			
	<u>no</u>	type	rate	<u>mid</u>	no	amount	no	mid	no	mid
0	100	'current'	NULL	0000	100	220.00				
	101	'deposit'	8.50	0001	102	2520.00				
	102	'deposit'	8.50							
1							100	0000	101	0001
							100	0001	102	0000
							101	0000	102	0001

# Example of since-product

$t$	account			movement			$(\pi_{no} \text{ account}) \bowtie (\pi_{mid} \text{ movement})$			
	<u>no</u>	type	rate	<u>mid</u>	no	amount	no	mid	no	mid
0	100	'current'	NULL	0000	100	220.00				
	101	'deposit'	8.50	0001	102	2520.00				
	102	'deposit'	8.50							
1	100	'current'	NULL	0002	101	100.00	100	0000	101	0001
	101	'deposit'	8.25	0003	104	1000.00	100	0001	102	0000
	103	'current'	NULL				101	0000	102	0001
	104	'current'	NULL							
2							100	0002	104	0002
							100	0003	104	0003
							101	0002	100	0000
							101	0003	100	0001
							103	0002	101	0000
							103	0003	101	0001

## Worksheet: The Since-Product Operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

# Worksheet: The Since-Product Operator

loc <sub>a</sub>	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

loc <sub>b</sub>	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

time
<u>time</u>
0

$t = 0$

loc <sub>a</sub>	
<u>name</u>	town
Peter	London
Jim	Edinburgh

loc <sub>b</sub>	
<u>name</u>	town
Peter	London
Jim	Edinburgh

time
<u>time</u>
1

$t = 1$

loc <sub>a</sub>	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

loc <sub>b</sub>	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

time
<u>time</u>
2

$t = 2$

loc <sub>a</sub>	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

loc <sub>b</sub>	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

time
<u>time</u>
3

$t = 3$

# Worksheet: The Since-Product Operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

$\text{eval}(\text{loc}_a \overset{s}{\times} \text{loc}_b, 2)$

$\text{loc}_a.\text{name}$	$\text{loc}_a.\text{town}$	$\text{loc}_b.\text{name}$	$\text{loc}_b.\text{town}$
Peter	London	Peter	London
Jim	Edinburgh	Peter	London
Peter	London	Jim	Edinburgh
Jim	Edinburgh	Jim	Edinburgh
Peter	London	Fred	Manchester
Jim	Edinburgh	Fred	Manchester

## Worksheet: The Since-Product Operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

$\text{eval}(\text{loc} \bowtie (\sigma_{\text{time}=0} \text{time}), 3)$

name	town	time
Peter	London	0

Find who has been working in the same place since time 0

## Worksheet: The Since-Product Operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

$\text{eval}((\pi_{\text{name}} \text{loc}) \overset{\times}{\bowtie} \sigma_{\text{time}=0} \text{time}, 3)$

<u>name</u>	time
Peter	0
Jim	0

Find who has been working since time 0

## Worksheet: The Since-Product Operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

$\text{eval}(\pi_{\text{loc}_b.\text{town}}((\pi_{\text{town}} \sigma_{\text{town}='Glasgow'} \text{loc}_a) \bowtie \text{loc}_b), 4)$

<u>loc<sub>b</sub>.town</u>
London
Glasgow
Edinburgh
Bristol

Find towns that have had people working in them for any period during the period Glasgow has had people working in it

## Deriving other operators

- Rather like Cartesian product, since-product and until-product not very useful alone
- Form basis for defining other operators

### since-join ( $\overset{S}{\bowtie}$ )

$$eval(R \overset{S}{\bowtie} S, t) = eval(\sigma_{R.A=S.A}(R \overset{S}{\bowtie} S), t)$$

*Find movements of accounts still open until yesterday*

$$\pi_{no, mid, amount}(\pi_{no} \text{account} \overset{S}{\bowtie} \text{movement})$$

### until-join ( $\overset{U}{\bowtie}$ )

$$eval(R \overset{U}{\bowtie} S, t) = eval(\sigma_{R.A=S.A}(R \overset{U}{\bowtie} S), t)$$

# Example of since-join

<i>t</i>	account			movement			$\pi_{no,mid,amount}$ ( $\pi_{no} \text{ account } \bowtie_S \text{ movement}$ )		
	<u>no</u>	type	rate	<u>mid</u>	no	amount	no	mid	amount
0	100	'current'	NULL	0000	100	220.00			
	101	'deposit'	8.50	0001	102	2520.00			
	102	'deposit'	8.50						
1	100	'current'	NULL	0002	101	100.00	100	0000	220.00
	101	'deposit'	8.25	0003	104	1000.00	102	0001	2520.00
	103	'current'	NULL						
	104	'current'	NULL						
2	100	'current'	NULL	0004	104	-500.00	101	0002	100.00
	101	'deposit'	8.25	0005	105	500.00	104	0003	1000.00
	103	'current'	NULL	0006	100	100.23	100	0000	220.00
	104	'current'	NULL						
	105	'deposit'	8.50						

# Quiz 3: Using $\bowtie$

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

What is the result of  $Eval(\pi_{loc_b.name}(\pi_{name} \sigma_{name='John'} loc_a \bowtie loc_b), 4)$ ?

**A**

<u>name</u>
Peter
John
Fred
Mary
Jim

**B**

<u>name</u>
Peter
Fred
Mary
Jim

**C**

<u>name</u>
Peter
John
Mary

**D**

<u>name</u>
Peter

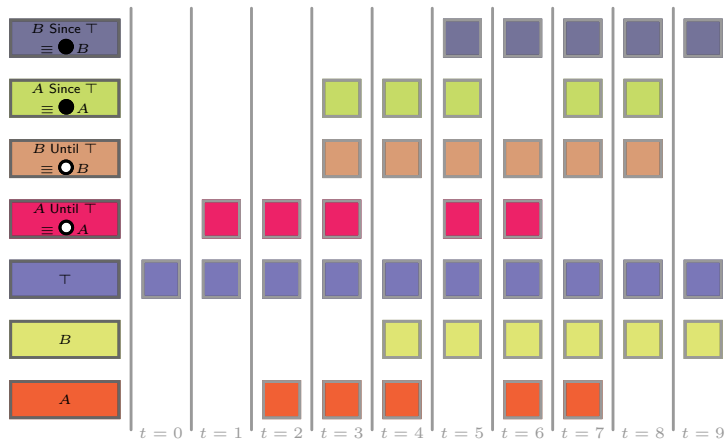
# US-Logic: Derived Operators $\circ$ and $\bullet$

■  $\circ A \equiv A \text{ Until } T$

■ Means 'is  $A$  true at the next time'

■  $\bullet A \equiv A \text{ Since } T$

■ Means 'is  $A$  true at the previous time'



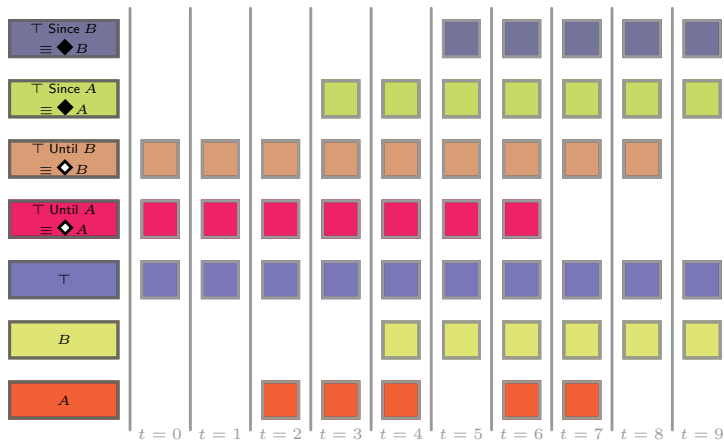
# US-Logic: Derived Operators $\diamond$ and $\blacklozenge$

■  $\diamond A \equiv \top \text{ Until } A$

■ Means 'is  $A$  true at some point in the future'

■  $\blacklozenge A \equiv \top \text{ Since } A$

■ Means 'is  $A$  true at some point in the past'



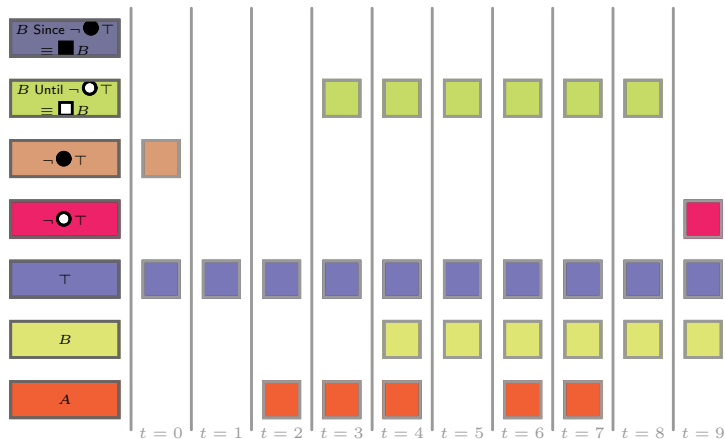
# US-Logic: Derived Operators $\square$ and $\blacksquare$

■  $\square A \equiv A \text{ Until } \neg \bigcirc T$

■ Means 'is  $A$  always true in the future'

■  $\blacksquare A \equiv A \text{ Since } \neg \bigcirc T$

■ Means 'is  $A$  always true in the past'



## Derived relational modal operators

temporal operator	name	equivalent using $\overset{\circ}{\times}$ and $\overset{\cup}{\times}$
$\bullet R$	previous	$R \overset{\circ}{\times} I$
$\blacklozenge R$	sometime in past	$I \overset{\circ}{\times} R$
$\blacksquare R$	always in past	$\pi_R(R \overset{\circ}{\times} \sigma_{time=0} time)$
$\circ R$	next	$R \overset{\cup}{\times} I$
$\blacklozenge R$	sometime in future	$I \overset{\cup}{\times} R$
$\square R$	always in future	$\pi_R(R \overset{\cup}{\times} \sigma_{time=n} time)$

# Modal operator: Sometime in past ◆

<i>t</i>	account			◆ account			◆ $\pi_{no}$ account
	<u>no</u>	type	rate	<u>no</u>	type	rate	<u>no</u>
0	100	'current'	NULL				
	101	'deposit'	8.50				
	102	'deposit'	8.50				
1	100	'current'	NULL	100	'current'	NULL	100
	101	'deposit'	8.25	101	'deposit'	8.50	101
	103	'current'	NULL	102	'deposit'	8.50	102
	104	'current'	NULL				
2	100	'current'	NULL	100	'current'	NULL	100
	101	'deposit'	8.25	101	'deposit'	8.25	101
	103	'current'	NULL	101	'deposit'	8.50	102
	104	'current'	NULL	102	'deposit'	8.50	103
	105	'deposit'	8.50	103	'current'	NULL	104
			104	'current'	NULL		

# Modal operator: Previous ●

<i>t</i>	account			●account		
	<u>no</u>	type	rate	<u>no</u>	type	rate
0	100	'current'	NULL			
	101	'deposit'	8.50			
	102	'deposit'	8.50			
1	100	'current'	NULL	100	'current'	NULL
	101	'deposit'	8.25	101	'deposit'	8.50
	103	'current'	NULL	102	'deposit'	8.50
	104	'current'	NULL			
2	100	'current'	NULL	100	'current'	NULL
	101	'deposit'	8.25	101	'deposit'	8.25
	103	'current'	NULL	103	'current'	NULL
	104	'current'	NULL	104	'current'	NULL
	105	'deposit'	8.50			

# Modal operator: Always in past ■

$t$	account	■ account	■ $\pi_{no,type}$ account
	<u>no</u> type rate	<u>no</u> type rate	<u>no</u> type
0	100 'current' NULL 101 'deposit' 8.50 102 'deposit' 8.50		
1	100 'current' NULL 101 'deposit' 8.25 103 'current' NULL 104 'current' NULL	100 'current' NULL 101 'deposit' 8.50 102 'deposit' 8.50	100 'current' 101 'deposit' 102 'deposit'
2	100 'current' NULL 101 'deposit' 8.25 103 'current' NULL 104 'current' NULL 105 'deposit' 8.50	100 'current' NULL	100 'current' 101 'deposit'

## Quiz 4: $\blacksquare$ modal logic operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

What is the result of  $Eval(\blacksquare loc, 3)$ ?

A

<u>name</u>	town
Peter	London

B

<u>name</u>	town
Peter	London
Jim	Edinburgh

C

<u>name</u>	town
Peter	London
Jim	Edinburgh
Jim	Glasgow

D

<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh
John	London
Jim	Glasgow
Mary	Edinburgh

## Quiz 5: ♦ modal logic operator

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

What is the result of  $Eval(\blacklozenge loc, 3)$ ?

A

<u>name</u>	town
Peter	London

B

<u>name</u>	town
Peter	London
Jim	Edinburgh

C

<u>name</u>	town
Peter	London
Jim	Edinburgh
Jim	Glasgow

D

<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh
John	London
Jim	Glasgow
Mary	Edinburgh

## Using the Derived Operators

Use ■ to find things always true

- *Find accounts that have always existed*  
■  $\pi_{no}$  account

Use ◆ to search the past for data

- *Find accounts that have made a withdrawal in the past*  
◆  $\pi_{no} \sigma_{amount < 0}$  movement
- *List the open accounts which have not made a withdrawal*  
 $\pi_{no}$  account  $-$  ◆  $\pi_{no} \sigma_{amount < 0}$  movement
- *List accounts which have opened for the first time*  
 $\pi_{no}$  account  $-$  ◆  $\pi_{no}$  account

Use ● to check what has just occurred

- *List accounts which have just opened or reopened*  
 $\pi_{no}$  account  $-$  ●  $\pi_{no}$  account

## Worksheet: Derived TRA Operators

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

# Worksheet: Derived TRA Operators

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

eval( $\blacklozenge$  loc, 3)

name	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh
Jim	Edinburgh
Fred	Manchester

## Worksheet: Derived TRA Operators

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

$\text{eval}(\blacksquare \pi_{\text{town}} \text{loc}, 3)$

town
London
Edinburgh

# Worksheet: Derived TRA Operators

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

$\text{eval}(\pi_{\text{loc}_a.\text{name}} \sigma_{\text{loc}_a.\text{town} \neq \text{loc}_b.\text{town} \wedge \text{loc}_a.\text{name} = \text{loc}_b.\text{name}} \blacklozenge(\text{loc}_a \times \blacklozenge \text{loc}_b), 4)$

loc<sub>a</sub>.name

Jim

Mary

John

Fred

## Worksheet: Derived TRA Operators

loc	
<u>name</u>	town
Fred	Manchester
Peter	London
Jim	Edinburgh

$t = 0$

loc	
<u>name</u>	town
Peter	London
Jim	Edinburgh

$t = 1$

loc	
<u>name</u>	town
Peter	London
John	London
Jim	Glasgow
Mary	Edinburgh

$t = 2$

loc	
<u>name</u>	town
Peter	London
John	Bristol
Fred	Glasgow
Mary	London

$t = 3$

pairs of towns that a person has transferred directly between

$$\pi_{loc_a.town, loc_b.town} \sigma_{loc_a.town \neq loc_b.town \wedge loc_a.name = loc_b.name} \blacklozenge (loc_a \times \bullet loc_b)$$

people who have always worked in the same town

$$(\pi_{name} \blacklozenge loc) - (\pi_{loc_a.name} \sigma_{loc_a.town \neq loc_b.town \wedge loc_a.name = loc_b.name} \blacklozenge (loc_a \times \blacklozenge loc_b))$$