# Execution Traces as a Powerful Data Representation for Intelligent Tutoring Systems for Programming

*Benjamin Paaßen* Joris Jensen Barbara Hammer

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⇒ ITSs are desirable

# Data-Driven ITSs

(Gross et al. 2014; Hicks et al. 2015; Rivers and Koedinger 2015)

student state

$x_t$

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$$\begin{tikzcd} & x_t \arrow[d] \\ m \arrow[r] & \mathcal{N}(x_t) \end{tikzcd}$$

database similar states

# Data-Driven ITSs

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$$\begin{tikzcd}
 & \text{student state} & \\
 & x_t \arrow[d] \arrow[dr] & \\
m \arrow[r] & \mathcal{N}(x_t) \arrow[r] & y_t \\
\text{database} & \text{similar states} & \text{feedback}
\end{tikzcd}$$

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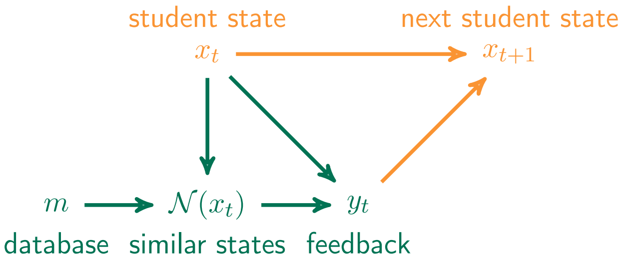

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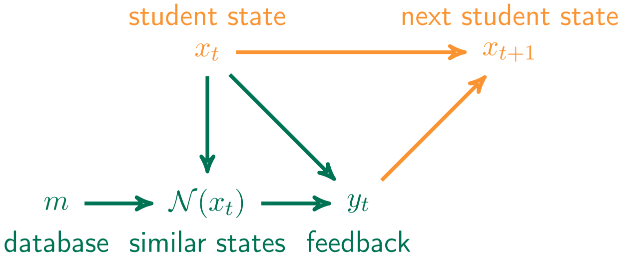


Main Research Questions:

# Data-Driven ITSs

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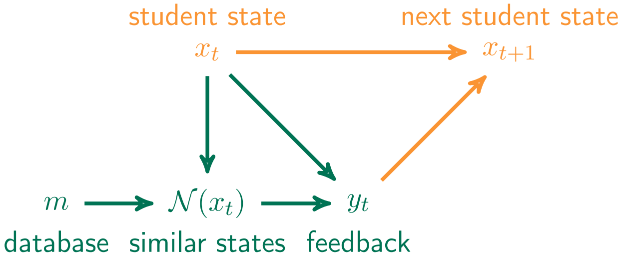


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- How to retrieve **similar states**?

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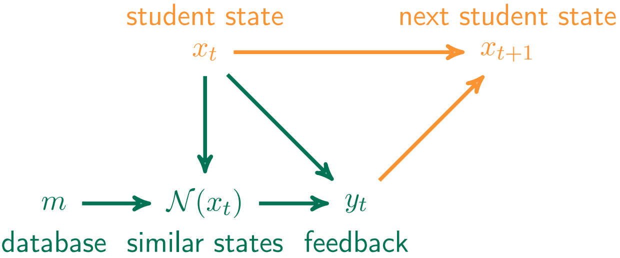


Main Research Questions:

- How to retrieve **similar states**?
- How to generate **feedback**? In particular: Error detection

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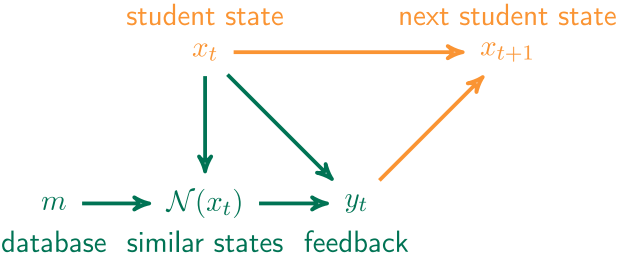


Main Research Questions:

- How to retrieve **similar states**?
- How to generate **feedback**? In particular: Error detection

⇒ Depends on **data representation**

# Data Representations: Syntax and Traces

# Syntax (1)

```
public static int[] bubblesort(int[] A) {
  final int l = 0;
  final int r = A.length - 1;
  for (int i = r; i > l; i--) {
    for (int j = l; j < i; j++) {
      if (A[j] > A[j + 1]) {
        final int tmp = A[j];
        A[j] = A[j + 1];
        A[j + 1] = tmp;
      }
    }
  }
  return A;
}
```

# Syntax (1)

```java
public static int[] bubblesort(int[] A) {
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      }
    }
  }
  return A;
}
```

```java
public static int[] insertionSort(int[] A) {
  final int l = 0;
  final int r = A.length - 1;
  for (int i = l; i < r; i++) {
    for (int j = i - 1; j >= l; j--) {
      if (A[j] > A[j + 1]) {
        final int tmp = A[j];
        A[j] = A[j + 1];
        A[j + 1] = tmp;
      }
    }
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      }
    }
  }
  return A;
}
```

# Syntax (2)

```java
public static int[] insertionSort(int[] A) {
  final int l = 0;
  final int r = A.length - 1;
  for (int i = l; i < r; i++) {
    for (int j = i - 1; j >= l; j--) {
      if (A[j] > A[j + 1]) {
        final int tmp = A[j];
        A[j] = A[j + 1];
        A[j + 1] = tmp;
      }
    }
  }
  return A;
}
```

```java
public static int[] insertionSort(int[] A) {
  final int l = 0;
  final int r = A.length - 1;
  insertionSort(A, l, r);
  return A;
}
private static void insertionSort(int[] A, int l, int r) {
  if (l < r) {
    insertionSort(A, l, r - 1);
    insert(A, l, r);
  }
}
private static void insert(int[] A, int l, int r) {
  if (l < r) {
    if (A[r - 1] > A[r]) {
      final int tmp = A[r - 1];
      A[r - 1] = A[r];
      A[r] = tmp;
    }
    insert(A, l, r - 1);
  }
}
```

# Traces (1)

```
int[] bubblesort(int[] A) {
  final int l = 0;
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  for (int i = r; i > l; i--) {
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| |
|---|
| |

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      }
    }
  }
  return A;
}
```

| A | l |
|---|---|
| [4,7,2,1] | 0 |

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```
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        A[j + 1] = tmp;
      }
    }
  }
  return A;
}
```

| A | l | r |
|---|---|---|
| [4,7,2,1] | 0 | |
| [4,7,2,1] | 0 | 3 |

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```
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}
```

| A | l | r | i |
|---|---|---|---|
| [4,7,2,1] | 0 | | |
| [4,7,2,1] | 0 | 3 | |
| [4,7,2,1] | 0 | 3 | 3 |

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| A | l | r | i | j |
|---|---|---|---|---|
| [4,7,2,1] | 0 | | | |
| [4,7,2,1] | 0 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | |
| [4,7,2,1] | 0 | 3 | 3 | 0 |

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| A | l | r | i | j |
|---|---|---|---|---|
| [4,7,2,1] | 0 | | | |
| [4,7,2,1] | 0 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | |
| [4,7,2,1] | 0 | 3 | 3 | 0 |
| ... | | | | |

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```

| A | l | r | i | j | tmp |
|---|---|---|---|---|---|
| [4,7,2,1] | 0 | | | | |
| [4,7,2,1] | 0 | 3 | | | |
| [4,7,2,1] | 0 | 3 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | 0 | |
| ... | | | | | |
| [4,7,2,1] | 0 | 3 | 3 | 1 | 7 |

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}
```

| A | l | r | i | j | tmp |
|---|---|---|---|---|---|
| [4,7,2,1] | 0 | | | | |
| [4,7,2,1] | 0 | 3 | | | |
| [4,7,2,1] | 0 | 3 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | 0 | |
| ... | | | | | |
| [4,7,2,1] | 0 | 3 | 3 | 1 | 7 |
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```

| A | l | r | i | j | tmp |
|---|---|---|---|---|---|
| [4,7,2,1] | 0 | | | | |
| [4,7,2,1] | 0 | 3 | | | |
| [4,7,2,1] | 0 | 3 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | 0 | |
| ... | | | | | |
| [4,7,2,1] | 0 | 3 | 3 | 1 | 7 |
| [4,2,2,1] | 0 | 3 | 3 | 1 | 7 |
| [4,2,7,1] | 0 | 3 | 3 | 1 | 7 |

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| A | l | r | i | j | tmp |
|---|---|---|---|---|---|
| [4,7,2,1] | 0 | | | | |
| [4,7,2,1] | 0 | 3 | | | |
| [4,7,2,1] | 0 | 3 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | 0 | |
| ... | | | | | |
| [4,7,2,1] | 0 | 3 | 3 | 1 | 7 |
| [4,2,2,1] | 0 | 3 | 3 | 1 | 7 |
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```

| A | l | r | i | j | tmp |
|---|---|---|---|---|---|
| [4,7,2,1] | 0 | | | | |
| [4,7,2,1] | 0 | 3 | | | |
| [4,7,2,1] | 0 | 3 | 3 | | |
| [4,7,2,1] | 0 | 3 | 3 | 0 | |
| ... | | | | | |
| [4,7,2,1] | 0 | 3 | 3 | 1 | 7 |
| [4,2,2,1] | 0 | 3 | 3 | 1 | 7 |
| [4,2,7,1] | 0 | 3 | 3 | 1 | 7 |

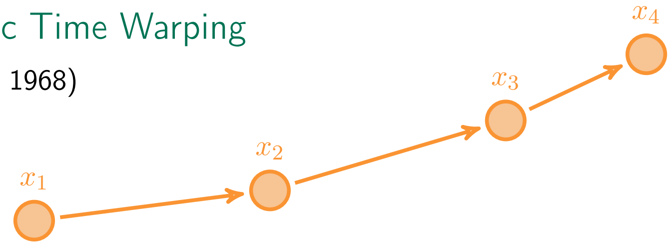
# Traces (2)

| *Bubble* | *Insertion* | recursive |
|---|---|---|
| $[4, 7, 2, 1]$ | $[4, 7, 2, 1]$ | $[4, 7, 2, 1]$ |
| $[4, 2, 7, 1]$ | $[4, 2, 7, 1]$ | $[4, 2, 7, 1]$ |
| $[4, 2, 1, 7]$ | $[2, 4, 7, 1]$ | $[2, 4, 7, 1]$ |
| $[2, 4, 1, 7]$ | $[2, 4, 1, 7]$ | $[2, 4, 1, 7]$ |
| $[2, 1, 4, 7]$ | $[2, 1, 4, 7]$ | $[2, 1, 4, 7]$ |
| $[1, 2, 4, 7]$ | $[1, 2, 4, 7]$ | $[1, 2, 4, 7]$ |

# Comparing Traces: Dynamic Time Warping

# Dynamic Time Warping

(Vintsyuk 1968)



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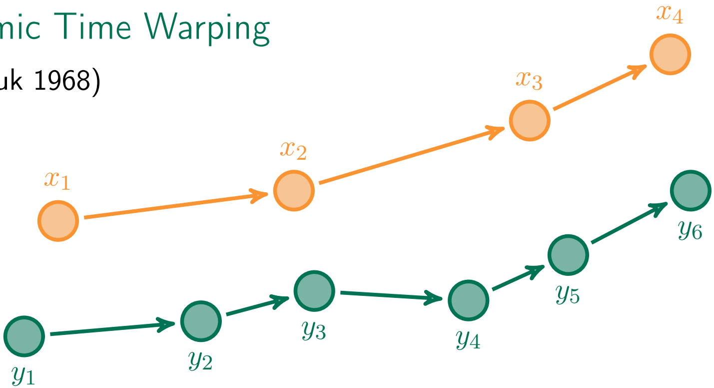

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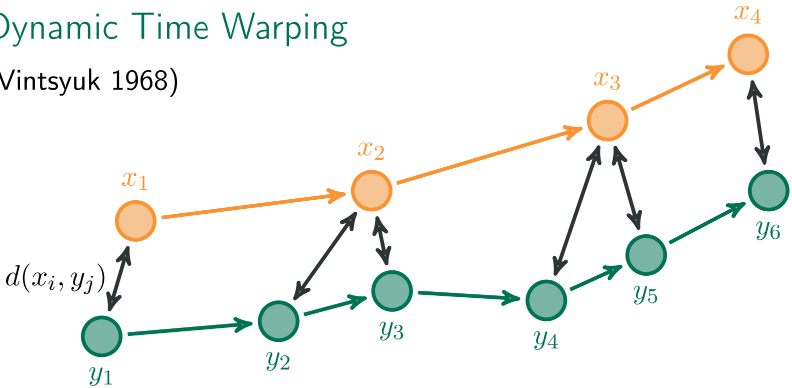

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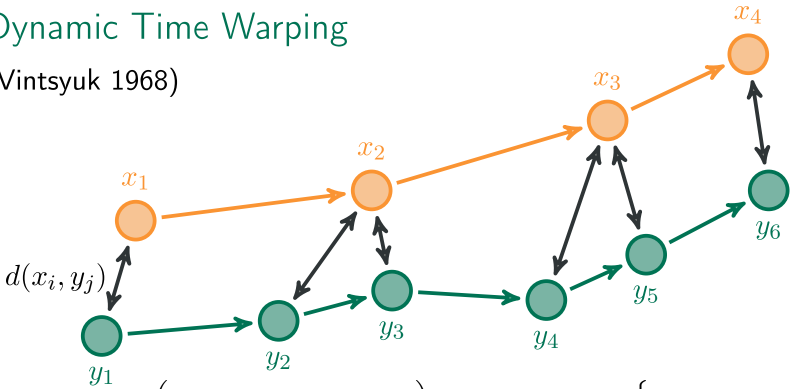


$$D_{\text{DTW}}\Big((x_1,\ldots,x_i),(y_1,\ldots,y_j)\Big) := d(x_i,y_j) + \min\Big\{ D_{\text{DTW}}\Big((x_1,\ldots,x_{i-1}),(y_1,\ldots,y_{j-1})\Big), D_{\text{DTW}}\Big((x_1,\ldots,x_{i-1}),(y_1,\ldots,y_j)\Big), D_{\text{DTW}}\Big((x_1,\ldots,x_i),(y_1,\ldots,y_{j-1})\Big)\Big\}$$

# Dynamic Time Warping: Example

| | |
|---|---|
| [4,7,2,1] | [4,7,2,1] |
| [4,7,2,1] | [4,2,2,1] |
| [4,7,2,1] | [4,2,7,1] |
| [4,2,2,1] | [4,2,7,1] |
| [4,2,7,1] | [2,2,7,1] |
| [4,2,7,1] | [2,4,7,1] |
| [4,2,7,1] | |
| [4,2,1,1] | |
| [4,2,1,7] | |

# Dynamic Time Warping: Example

| | | |
|---|---|---|
| [4,7,2,1] | $d(x_i, y_j) = 0$ | [4,7,2,1] |
| [4,7,2,1] | | [4,2,2,1] |
| [4,7,2,1] | | [4,2,7,1] |
| [4,2,2,1] | | [4,2,7,1] |
| [4,2,7,1] | | [2,2,7,1] |
| [4,2,7,1] | | [2,4,7,1] |
| [4,2,7,1] | | |
| [4,2,1,1] | | |
| [4,2,1,7] | | |

# Dynamic Time Warping: Example

| | | |
|---|---|---|
| [4,7,2,1] | $d(x_i,y_j) = 0$ | [4,7,2,1] |
| [4,7,2,1] | $d(x_i,y_j) = 0$ | [4,2,2,1] |
| [4,7,2,1] | | [4,2,7,1] |
| [4,2,2,1] | | [4,2,7,1] |
| [4,2,7,1] | | [2,2,7,1] |
| [4,2,7,1] | | [2,4,7,1] |
| [4,2,7,1] | | |
| [4,2,1,1] | | |
| [4,2,1,7] | | |

# Dynamic Time Warping: Example

| | | |
|---|---|---|
| [4,7,2,1] | $d(x_i,y_j) = 0$ | [4,7,2,1] |
| [4,7,2,1] | $d(x_i,y_j) = 0$ | [4,2,2,1] |
| [4,7,2,1] | $d(x_i,y_j) = 0$ | [4,2,7,1] |
| [4,2,2,1] | | [4,2,7,1] |
| [4,2,7,1] | | [2,2,7,1] |
| [4,2,7,1] | | [2,4,7,1] |
| [4,2,7,1] | | |
| [4,2,1,1] | | |
| [4,2,1,7] | | |

# Dynamic Time Warping: Example

[4,7,2,1] $d(x_i,y_j) = 0$ [4,7,2,1]

[4,7,2,1] $d(x_i,y_j) = 0$ [4,2,2,1]

[4,7,2,1] $d(x_i,y_j) = 0$ [4,2,7,1]

[4,2,2,1] [4,2,7,1]

[4,2,7,1] $d(x_i,y_j) = 0.5$ [2,2,7,1]

[4,2,7,1] [2,4,7,1]

[4,2,7,1]

[4,2,1,1]

[4,2,1,7]

# Dynamic Time Warping: Example

[4,7,2,1] — $d(x_i,y_j) = 0$ — [4,7,2,1]

[4,7,2,1]

[4,7,2,1]

[4,2,2,1] — $d(x_i,y_j) = 0$ — [4,2,2,1]

[4,2,7,1] — $d(x_i,y_j) = 0$ — [4,2,7,1]

[4,2,7,1] — [4,2,7,1]

[4,2,7,1] — $d(x_i,y_j) = 0.5$ — [2,2,7,1]

[4,2,1,1] — $d(x_i,y_j) = 1$ — [2,4,7,1]

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$\Rightarrow$ Subject to ongoing research

# Experiments

# Overview

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- TCS Alignment Toolbox (Paaßen, Mokbel, and Hammer 2015a)

# Datasets

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(Mokbel et al. 2013)

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# Strategy Classification: Results

| method | palindromes | sorting |
|---|---|---|
| syntax | 0.8750 (0.1581) | 0.8118 (0.0676) |
| traces | 0.9792 (0.0510) | 0.9535 (0.0403) |

mean classification accuracy (and standard deviation) across cross-validation trials

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mean classification accuracy (and standard deviation) across cross-validation trials

$\Rightarrow$ Significant difference for **sorting** dataset ($p < 0.01$).

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Introduce **erroneous counterparts** for sorting programs, such that:

- program still compiles and executes without exception
- produces the wrong (e.g. unsorted) output
- still is plausible

# Error Classification: Results

| method | accuracy |
|---|---|
| syntax | 0.2112 (0.1073) |
| traces | 0.8608 (0.0856) |

mean classification accuracy (and standard deviation) across cross-validation trials on the sorting dataset with artificial errors.

# Error Detection: Syntax

```
public static int[] bubblesort(int[] A) {
  final int l = 0;
  final int r = A.length - 1;
  for (int i = r; i > l; i--) {
    for (int j = l; j >= 0; j--) {
      if (A[j] > A[j + 1]) {
        final int tmp = A[j];
        A[j] = A[j + 1];
        A[j + 1] = tmp;
      }
    }
  }
  return A;
}
```

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public static int[] bubblesort(int[] A) {
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```
[4,7,2,1]
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[4,7,7,1]
[4,2,7,1]
[4,2,7,1]
[4,2,7,1]
[4,2,1,1]
[4,2,1,7]
```

# Error Detection: Traces

| | |
|---|---|
| [4,7,2,1] | [4,7,2,1] |
| [4,7,2,1] | [4,2,2,1] |
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| [4,7,7,1] | [4,2,7,1] |
| [4,2,7,1] | [2,2,7,1] |
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# Error Detection: Results

| method | precision | recall |
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| syntax | 0.1031 (0.0859) | 0.1335 (0.1004) |

mean precision and recall (with standard deviation in brackets) on the **sorting** dataset

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$\Rightarrow$ Significant difference in F1 score ($p < 0.0001$)

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Thank you for your attention!

# Literature I

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