Data allocation on disks with solution reconfiguration (problems, heuristics)

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The paper addresses problem of data allocation in two-layer computer storage while taking into account dynamic digraphs over computing tasks. The basic version of data file allocation on parallel hard magnetic disks is considered as special bin packing model. Two problems of the allocation solution reconfiguration (restructuring) are suggested: (i) one-stage restructuring model, (ii) multistage restructuring models. Solving schemes are based on simplified heuristics. Numerical examples illustrate problems and solving schemes.

Keywords: data allocation, hard disk, combinatorial optimization, reconfiguration, heuristics

Contents

1 Introduction 1
2 General problems types 2
3 Allocation of files on hard magnetic disks 4
3.1 Problem statement ................................................................. 4
3.2 Basic simple ideas for solving schemes ..................................... 5
3.3 Example of file allocation ....................................................... 6
4 Reconfiguration (restructuring) of file allocation solutions 6
4.1 One-stage restructuring ......................................................... 6
4.2 Multistage restructuring ....................................................... 8
5 Conclusion 9
6 Acknowledgments 9

1. Introduction

In management/planning of hierarchical, distributed computer systems, problems of tasks/data placement in storage have been studied many years as allocation of objects (tasks, jobs, balls, data files) into set of resources (e.g., servers, computers, machines, bins, urns) (e.g., [12,5,13,14,16]). Mathematical modeling of the problems is often based on stochastic models (e.g., Markov processes) (e.g., [5] and combinatorial optimization models (e.g., multiple knapsack problems, location/assignment models, bin packing problems) (e.g., [3,14]). One of the data placement problem is targeted to file allocation on a hard magnetic disk with moving disk driver heads (e.g., [3,6,7,12]). Usually, the study of this kind of problems (as control of two-level storage) is based on the following approaches: (a) stochastic approach (e.g., [3,7]), (b) approximation solving schemes (e.g., [5,13]); (c) heuristic and metaheuristic solving schemes (e.g., [3,6,7]).

In this paper, problem of data file allocation in two-layer computer memory and parallel memories (disks) at the second layer while taking into account dynamic digraphs over computing tasks. The author version of file allocation on hard magnetic disks is examined as a special version of bin packing.

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problem. This allocation problem is considered as the basic one. In addition, two optimization problems as reconfiguration of allocation solution(s) are examined: (i) one-stage restructuring [9,11,15], (ii) multi-stage restructuring [9,11]. Some basic simple heuristic ideas are described and corresponding simplified solving schemes are used. A numerical example illustrates the file allocation problems, reconfiguration of allocation solutions, and simple solving schemes (heuristics).

2. General problems types

Our generalized description of the considered problem is the following (Fig. 1):

\[
\text{Problem : } < M_{\text{proc}} - \alpha | M_o - \beta | M_e - \gamma >
\]

where \( M_{\text{proc}} \) corresponds to processors (\( \alpha \) is the number of parallel processors); \( M_o \) corresponds to operation memory (\( \beta \) is the number of parallel operation memories); \( M_e \) corresponds to external memory (\( \gamma \) is the number of parallel external memories, e.g., disks).

Generally, the following six basic computer hierarchy cases can be examined:

(a) **Problem 1**: 1 processor, 1 memory, 1 disk \(< M_{\text{proc}} - 1 | M_o - 1 | M_e - 1 > \) (Fig. 2a) (e.g., [8,10]);

(b) **Problem 2**: 1 processor, 1 memory, \( \gamma \) disks \(< M_{\text{proc}} - 1 | M_o - 1 | M_e - \gamma > \) (Fig. 2b) (e.g., [12]);

(c) **Problem 3**: 1 processor, \( \beta \) memory, \( \gamma \) disks \(< M_{\text{proc}} - 1 | M_o - \beta | M_e - \gamma > \) (Fig. 2c, \( \beta = \gamma \));

(d) **Problem 4**: \( \alpha \) processors, 1 memory, 1 disk \(< M_{\text{proc}} - \alpha | M_o - 1 | M_e - 1 > \) (Fig. 3a);

(e) **Problem 5**: \( \alpha \) processors, \( \beta \) memories, 1 disk \(< M_{\text{proc}} - \alpha | M_o - \beta | M_e - 1 > \) (Fig. 3b, \( \alpha = \beta \));

(f) **Problem 6**: \( \alpha \) processors, \( \beta \) memories, \( \gamma \) disks \(< M_{\text{proc}} - \alpha | M_o - \beta | M_e - \gamma > \) (Fig. 3c, \( \alpha = \beta = \gamma \)).

Fig. 1. General frameworks

Fig. 2. One-processor problems 1, 2, and 3

Fig. 4 illustrates one-stage allocation of data files on hard magnetic disks as bin packing problem. The following designations are used: (a) digraph \( D = (T,R) \), where \( T \) is the set of computing tasks, \( R \) is precedence relation as a set of arcs over the computing tasks above; (b) data files and processing graph
over them $G = \langle Q, E_1, E_2 \rangle$, where $Q$ is the set of data files under processing, $E_1$ is precedence binary relation over the files (i.e., a set of arcs), $E_2$ is symmetric binary relation of common processing of data files (i.e., concurrently, a set of edges).

Further, it is reasonable to examine time sequence $< t_1, ..., t_j, ..., t_k >$ and the corresponding sequence of computing tasks digraphs: $< D^1 = (T^1, R^1), ..., D^j = (T^j, R^j), ..., D^k = (T^k, R^k) >$ (Fig. 5). Evidently, the computing tasks digraph sequence requires allocation of data files on disks.

The sequence of data files processing graphs is:

$G = \langle G^1 = (Q^1, E_1^1, E_2^1) \rightarrow ... \rightarrow G^j = (Q^j, E_1^j, E_2^j) \rightarrow ... \rightarrow G^k = (Q^k, E_1^k, E_2^k) >$, 

Fig. 3. Multi-processor problems 4, 5, and 6

Fig. 4. File location on disks

Fig. 5. Processing a sequence of computing task digraphs
where $Q$ is the set of data files, $E$ is the set of edges/arcs, $G = (Q, E)$ is the general file processing graph, $G^j = (A^j, E^j_1, E^j_2)$ is the file processing graph at time $t_j$, $A^j \subseteq A$, $E^j_1 \subseteq E_1$, $E^j_2 \subseteq E_2$.

Note, the graph chains can be generalized to examine graph networks, e.g., $\mathcal{D} = (D, V)$, where $D = \{D^j, j = 1, k\}$ is the set of computing task digraphs, $V$ is a set of arcs (i.e., precedence constraint over the set of computing task digraphs). Here many combinatorial optimization models can be used as auxiliary problems, for example (e.g., [4]): (i) multiple knapsack models, (ii) assignment/allocation models, (iii) bin packing models, and (iv) covering models.

3. Allocation of files on hard magnetic disks

3.1. Problem statement

Our problem for data file allocation on hard magnetic disks has been suggested in [12] as follows. Let $Q = \{1, ..., i, ..., n\}$ be a set of data files, $L = \{1, ..., \xi, ..., \gamma\}$ be a set of external memories (hard disks). Each disk $\xi \in L$ has a number of free disk tracks $W_\xi$ (i.e., disk size). The required memory size for each file (i.e., the required number of disk tracks) $\forall i \in Q$ is: $d_i$. Evidently, the global memory size constraint is: $\sum_{i=1}^{n} d_i \leq \sum_{\xi=1}^{\gamma} W_\xi$.

First, partitioning the files on disks is (without intersections): $X = \{X_1, ..., X_\xi, ..., X_\gamma\}$ ($|X_\xi \cup X_\gamma| = 0, \forall \xi_1, \xi_2 \in Q$), where set of files $X_\xi$ ($X_\xi \subseteq Q$) is located on disk $\xi$ and the size constraint for each disk $\xi$ is: $\sum_{\eta \in X_\xi} d_\eta \leq W_\xi, \forall \xi \in L$. In addition, at each disk $\xi$ the corresponding files $X_\xi$ are ordered to get a linear ordering: $\overline{X_\xi}$. Thus, the global solution is (file allocation): $\overline{X} = \{\overline{X_1}, ..., \overline{X_\xi}, ..., \overline{X_\gamma}\}$.

Second, processing the files is defined by matrix movement probabilities (from one file $i_1$ to another file $i_2$, this is defined by processing graph): $\Phi(G) = ||\phi_{i_1,i_2}||_{i_1,i_2=1}^n$, $i_1, i_2 \in Q$, where $\phi_{i_1,i_2}$ is a stationary probability of movement from file $i_1$ to file $i_2$ (in data file processing graph $G$).

Let $E_3$ be a symmetric binary relation of joint file processing (integration of $E_1$ and $E_2$). For example, $E_3$ can be defined by the rule: $((i_1, i_2) \in E_1) \cup ((i_1, i_2) \in E_2) \Rightarrow (i_1, i_2) \in E_3 \forall i_1, i_2 \in Q$.

Note location of files at different disks leads to concurrent processing the files without movement of disk drive head. Finally, the considered objective function for allocation of files $\overline{X}$ is:

$$\min \Psi(\overline{X}) = \sum_{i_1 \in X_{\xi_1}, i_2 \in X_{\xi_2}, \xi_1=\xi_2} \phi_{i_1,i_2} p_{i_1,i_2}(\overline{X})$$

where $p_{i_1,i_2}(\overline{X})$ is a cost of disk drive head movement from file $i_1$ to file $i_2$ for solution $\overline{X}$.

Note, counting of $p_{i_1,i_2}(\overline{X})$ is a complicated problem and simplified methods are often applied.

In Fig. 6, the problem of file re-allocation on disks is illustrated.

![Fig. 6. Illustration for re-allocation of data files on disks](image-url)
Here the following notations are used:
1. Two time moments: \( t_1 \) and \( t_2 \) \((t_2 > t_1)\).
2. Digraphs over computing tasks (for \( t_1 \) and \( t_2 \)):
   (a) for \( t_1 \): digraph \( D^1 = (T^1, R^1) \), where \( T^1 \) is the set of tasks, \( R^1 \) is the precedence relation as a set of arcs over the tasks above;
   (b) for \( t_2 \): \( D^2 = (T^2, R^2) \) (components are analogical ones);
   (c) \( T^1, T^2 \subseteq T \), \( T \) is the general set of tasks.
3. Data files processing graphs (for \( t_1 \) and \( t_2 \)):
   (a) for \( t_1 \): graph \( G^1 = < Q^1, E^1_1, E^1_2 > \), where \( Q^1 \) is the set of files under processing at the time \( t_1 \), \( E^1_1 \) is the binary relation as precedence over the files \( t \) (i.e., a set of arcs), \( E^1_2 \) is the binary relation of concurrent processing over the files \( t \) (i.e., a set of edges);
   (b) for \( t_2 \): \( G^2 = < Q^2, E^2_1, E^2_2 > \) (components are analogical ones);
   (c) \( Q^1, Q^2 \subseteq Q \), \( Q \) is the general set of files.
4. Allocation of files (for \( t_1 \) and \( t_2 \)): \( Q^1 \) into \( n \) disks (i.e., bins): \( X^1, X^2 \).

Thus, Fig. 6 illustrates re-allocation of files: \( X^1 \Rightarrow X^2 \).

### 3.2. Basic simple ideas for solving schemes

The basic simplified ideas for file allocation are the following (e.g., [6,12]):
1. Small and interconnected files can by integrated (condensing) (this leads to reduction of the problem dimension).
2. Interconnected files have to be located on different disks (this leads to parallel processing without movement of hard disk heads).
3. Interconnection relations can be integrated into a total integrated relations and this relation is a basis to detect interconnected components in graph over files as cliques or quasi-cliques (communities). It is reasonable to obtain the communities with cardinalities \( \leq \gamma \) (this is the number of disks/bins). Thus, the examined problem consists in partitioning the initial graph over files into “good” interconnected subgraph.
4. For each file community it is reasonable to locate its elements into different bins.
5. Local optimization techniques can be used to improve the obtained solution.
Clearly, the solving framework (metaheuristic) can be based on the ideas.

### 3.3. Example of file allocation

The simplified numerical example is depicted in Fig. 7 (as packing of items/files into disks/bins):
(i) 8 data files \( Q^1 = \{1, 2, 3, 4, 5, 6, 7, 8\} \), (ii) three disks (bins), (iii) data processing graph \( G^1 = < Q^1, E^1_1, E^1_2 > \) where relations \( E^1_1, E^1_2 \) are presented in Table 1 and Table 2.

For the simplicity, the following is assumed: (a) file sizes are equals, (b) ordering the files at the same disk is not considered, (c) the cost of disk head movement from one file to another file at the same disk...
equals 1.0, (d) probabilities of movement from one file to another file, initiated by processing graph, are equal. Table 3 contains integrated relation $E^3_1$.

| $i_1/i_2$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------|---|---|---|---|---|---|---|---|
| 1          |   | * | 1 | 1 |   |   |   |   |
| 2          |   | -1| * |   |   |   |   |   |
| 3          |   | -1| * |   |   |   |   |   |
| 4          |   |   | * | 1 |   |   |   |   |
| 5          |   |   | -1| * |   |   |   |   |
| 6          |   |   |   |   |* |   |   |   |
| 7          |   |   |   |   |   |   |* |   |
| 8          |   |   |   |   |   |   |   |* |

Table 2. Concurrency relation $E^1_2$

| $i_1/i_2$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------|---|---|---|---|---|---|---|---|
| 1          |   | * |   |   |   |   |   |   |
| 2          |   |   | * | 1 |   |   |   |   |
| 3          |   |   | 1 | * |   |   |   |   |
| 4          |   |   |   |   |* |   |   |   |
| 5          |   |   |   |   |   |   |* |   |
| 6          |   |   |   |   |   | 1 | 1 |   |
| 7          |   |   |   |   |   |   | 1 | * |
| 8          |   |   |   |   |   |   |   | 1 |

Table 3. Integrated relation $E^3_1$

| $i_1/i_2$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------|---|---|---|---|---|---|---|---|
| 1          |   | * | 1 | 1 |   |   |   |   |
| 2          |   | 1 | * | 1 |   |   |   |   |
| 3          |   | 1 | 1 | * |   |   |   |   |
| 4          |   |   |   |   |* | 1 |   |   |
| 5          |   |   |   |   |   | 1 | * |   |
| 6          |   |   |   |   |   |   |* | 1 |
| 7          |   |   |   |   |   |   |   | 1 |
| 8          |   |   |   |   |   |   |   | 1 |

Relation $E^3_1$ is a basis to detect 3 interconnected components as cliques or quasi-cliques (by processing) as follows: \{1, 2, 3\}, \{6, 7, 8\}, \{4, 5\}.

Further, it is reasonable to locate elements of each clique above into different bins/disk. Thus, the file allocation solution is (without file ordering on each disk) (Fig. 7): $X^1 = \{1, 4, 6\}$, $X^2 = \{2, 5, 7\}$, $X^3 = \{3, 8\}$, i.e., $X^1 = \{X^1_1, X^1_2, X^1_3\}$ and the corresponding value of objective function is: $\Psi(X^1) = 0$.

4. Reconfiguration (restructuring) of file allocation solutions

In this section, two problems of solution reconfiguration are described: one-stage restructuring and two-stage restructuring. This restructuring approach is applied for data file allocation solutions (i.e., reconfiguration of allocation solutions). It is assumed the cost of file relocation operation from one disk to another disk is equal 1.0. The allocation problem from previous section is considered as the stage 1 ($t = t_1$) with corresponding allocation solution $X^1$ (Fig. 7).

4.1. One-stage restructuring

Here a next time stage (stage 2, $t = t_2$) is considered (Fig. 8, Table 4, Table 5). Integrated relation over files is contained in Table 6. 3 interconnected components are: \{1, 4, 5\}, \{2, 3, 6\}, \{7, 8\}.

The corresponding solution is (Fig. 8, $t = t_2$): $X^2_1 = \{1, 2, 7\}$, $X^2_2 = \{4, 3, 8\}$, $X^2_3 = \{5, 6\}$; i.e., $X^2 = \{X^2_1, X^2_2, X^2_3\}$ and the corresponding value of objective function is: $\Psi(X^2) = 0$.

Thus, the following restructuring problem is examined (ordering of file on disk is not considered)
Modify solution $X^1$ into restructured solution $X^{2*}$ such that
\[
\min \rho(X^{2*}, X^2) = |\Phi(X^{2*}) - \Phi(X^2)| \quad \text{(proximity)} \\
\text{s.t. } h(X^1 \Rightarrow X^{2*}) \leq 2.0 \quad \text{(modification cost)}.
\]

Note, restructuring process $X^1 \Rightarrow X^2$ consists of the following file re-locations operations: (i) file 4 is relocated from disk 1 into disk 3, (ii) file 5 is relocated from disk 2 into disk 1, and (iii) file 1 is relocated from disk 1 into disk 2. The cost of the relocation problem is: $h(X^1 \Rightarrow X^2) = 3.0$. 

\begin{table}[h]
\centering
\begin{tabular}{c|cccccccc}
\hline
$i_1/i_2$ & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
1 & * & 1 & 1 &   &   &   &   &   \\
2 & * & * & 1 &   &   &   &   &   \\
3 & * & * & 1 &   &   &   &   &   \\
4 & -1 & * & 1 &   &   &   &   &   \\
5 & -1 & -1 & * &   &   &   &   &   \\
6 & -1 & -1 & * &   &   &   &   &   \\
7 &   &   &   &   &   &   &   &   \\
8 &   &   &   &   &   &   &   &   \\
\hline
\end{tabular}
\caption{Precedence relation $E^1_2$}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{c|cccccccc}
\hline
$i_1/i_2$ & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
1 & * & 1 &   &   &   &   &   &   \\
2 & * & 1 &   &   &   &   &   &   \\
3 & 1 & * &   &   &   &   &   &   \\
4 &   &   &   &   &   &   &   &   \\
5 &   &   &   &   &   &   &   &   \\
6 &   &   &   &   &   &   &   &   \\
7 &   &   &   &   &   &   &   &   \\
8 &   &   &   &   &   &   &   &   \\
\hline
\end{tabular}
\caption{Concurrency relation $E^2_3$}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{c|cccccccc}
\hline
$i_1/i_2$ & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
1 & * & 1 & 1 &   &   &   &   &   \\
2 & * & 1 & 1 &   &   &   &   &   \\
3 & 1 & * & 1 &   &   &   &   &   \\
4 & 1 & * & 1 &   &   &   &   &   \\
5 & 1 & 1 & * &   &   &   &   &   \\
6 & 1 & 1 & * &   &   &   &   &   \\
7 &   &   &   &   &   &   &   &   \\
8 &   &   &   &   &   &   &   &   \\
\hline
\end{tabular}
\caption{Integrated relation $E^3_4$}
\end{table}
Now the following restructuring process for $X^1 \Rightarrow X^2$ is examined: (i) file 5 is relocated from disk 2 into disk 1, (ii) file 1 is relocated from disk 1 into disk 2. The obtained restructured solution is: $X^{2*} = \{X_1^{2*}, X_2^{2*}, X_3^{2*}\}$ where $X_1^{2*} = \{4, 5, 6\}$, $X_1^{2*} = \{1, 2, 3\}$, $X_3^{2*} = \{3, 8\}$.

The cost of the relocation problem is: $h(X^1 \Rightarrow X^{2*}) = 2.0$, the corresponding value of objective function is: $\Psi(X^{2*}) = 1.0$ (here the disk head movement is needed from file 4 to file 5, $t = t_2$).

4.2. Multistage restructuring

Here a next time stage (stage 3, $t = t_3$) is considered (Fig. 9, Table 7, Table 8). Integrated relation over files is contained in Table 9. 3 interconnected components are: $\{1, 2, 4\}$, $\{3, 5, 6\}$, $\{7, 8\}$.

The corresponding solution is (Fig. 9, $t = t_3$): $X_1^3 = \{1, 3, 7\}$, $X_2^3 = \{2, 5, 8\}$, $X_3^3 = \{4, 6\}$, i.e, $X^3 = \{X_1^3, X_2^3, X_3^3\}$ and the corresponding value of objective function is: $\Psi(X^3) = 0$.

![Diagram](image-url)

Table 7. Precedence relation $E_3^1$

| $i_1/i_2$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-----------|---|---|---|---|---|---|---|---|
| 1         | * | 1 | 1 |   |   |   |   |   |
| 2         | -1| * |   |   |   |   |   |   |
| 3         |   | * |   |   |   |   |   |   |
| 4         | -1| * |   |   |   |   |   |   |
| 5         |   |   |   |   |   |   |   |   |
| 6         |   |   |   |   |   |   | * |   |
| 7         |   |   |   |   |   | * | 1 |   |
| 8         |   |   |   |   |   | -1| * |   |

Table 8. Concurrency relation $E_3^2$

| $i_1/i_2$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-----------|---|---|---|---|---|---|---|---|
| 1         | * |   |   |   |   |   |   |   |
| 2         |   | * | 1 |   |   |   |   |   |
| 3         |   | * | 1 | 1 |   |   |   |   |
| 4         |   | 1 | * |   |   |   |   |   |
| 5         |   |   | 1 | * |   |   |   |   |
| 6         |   |   | 1 | 1 | * |   |   |   |
| 7         |   |   |   |   |   | * |   |   |
| 8         |   |   |   |   |   |   |   | * |
Note, restructuring process $X^2 \Rightarrow X^3$ consists of the following file re-locations operations: (i) file 4 is relocated from disk 2 into disk 3, (ii) file 5 is relocated from disk 3 into disk 2, (iii) file 3 is relocated from disk 2 into disk 1, and (iv) file 1 is relocated from disk 1 into disk 2. The cost of the relocation problem is: $h(X^2 \Rightarrow X^3) = 4.0$.

Now the following restructuring process for $X^{2*} \Rightarrow X^{3*}$ is examined: (i) file 3 is relocated from disk 3 into disk 1, (ii) file 2 is relocated from disk 2 into disk 3. The obtained restructured solution is: $X^{3*} = \{X_1^{3*}, X_2^{3*}, X_3^{3*}\}$ where $X_1^{3*} = \{4, 5, 6\}$, $X_2^{3*} = \{1, 3, 7\}$, $X_3^{3*} = \{2, 8\}$.

The cost of the relocation problem is: $h(X^{2*} \Rightarrow X^{3*}) = 2.0$, the corresponding value of objective function is: $\Psi(X^{3*}) = 1.0$ (here the disk head movement is needed from file 5 to file 6, $t = t_3$).

Finally, two 3-stage file allocation trajectory can be considered:

(i) trajectory consisting of local optimal solutions $S^{opt} = \langle X^1, X^2, X^3 >$, here total solution modification cost equals 7.0;

(ii) trajectory consisting of restructured solutions $S^{restr} = \langle X^1, X^{2*}, X^{3*} >$, here total solution modification cost equals 4.0 and proximity to optimal value of objective function at stage 2 and stage 3 will be equal 1.0 (this case corresponds to sequential solving strategy [11]).

Evidently, it is possible to manage the parameters of the restructuring process, i.e., by changes of the required constraint(s) for modification cost(s) for restructuring problems.

5. Conclusion

The paper contains description of data allocation in two-layer computer storage (several disks). Models and simplified heuristics were described. In addition, solution reconfiguration problems for data allocation on disks was suggested: (i) one-stage restructuring, (ii) multistage restructuring. It is necessary to point out other applications as allocation of objects into parallel resources, for example: (1) distributed computer systems (e.g., task allocation while taking into account tasks interconnection), (2) communication systems: (2.1) planning of multiple access communication channels (e.g., allocation of messages into subchannels while taking into account message interference), (2.2) planning of multiple beam antenna (e.g., allocation of messages into antenna subbeams while taking into account message interference), (2.3) connection of end-users and access points in communication systems.

The prospective future research directions are the following: (a) examination of the suggested problems with different file sizes, (b) taking into account uncertainty in models, (c) execution of computer experiments for analysis and comparison of various solving methods, (d) consideration of other application domains, and (e) usage of the described approaches in CS/engineering education.

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