Solving the $n_1 \times n_2 \times n_3$ Points Problem for $n_3 < 6$

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Abstract: In this paper, we show enhanced upper bounds of the nontrivial $n_1 \times n_2 \times n_3$ points problem for every $n_1 \leq n_2 \leq n_3 < 6$. We present new patterns that drastically improve the previously known algorithms for finding minimum-link covering paths, solving completely a few cases (e.g., $n_1 = n_2 = 3$ and $n_3 = 4$).

Keywords: Graph theory, Topology, Three-dimensional, Creative thinking, Link, Connectivity, Outside the box, Upper bound, Point, Game.

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1 Introduction

The $n_1 \times n_2 \times n_3$ points problem [12] is a three-dimensional extension of the classic nine dots problem appeared in Samuel Loyd’s Cyclopedia of Puzzles [1-9], and it is related to the well known NP-hard traveling salesman problem, minimizing the number of turns in the tour instead of the total distance traveled [1-15].

Given $n_1 \cdot n_2 \cdot n_3$ points in $\mathbb{R}^3$, our goal is to visit all of them (at least once) with a polygonal path that has the minimum number of line segments connected at their end-points (links or generically lines), the so called Minimum-link Covering Path [3-4-5-8]. In particular, we are interested in the best solutions for the nontrivial $n_1 \times n_2 \times n_3$ dots problem, where (by definition) $1 \leq n_1 \leq n_2 \leq n_3$ and $n_3 < 6$.

Let $h_l(n_1, n_2, n_3) \leq h(n_1, n_2, n_3) \leq h_u(n_1, n_2, n_3)$ be the length of the covering path with the minimum number of links for the $n_1 \times n_2 \times n_3$ points problem, we define the best known upper bound as $h_u(n_1, n_2, n_3) \geq h(n_1, n_2, n_3)$ and we denote as $h_l(n_1, n_2, n_3) \leq h(n_1, n_2, n_3)$ the current proved lower bound [12].

For the simplest cases, the same problem has already been solved [3-12]. Let $n_1 = 1$ and $n_2 < n_3$, we have that $h(n_1, n_2, n_3) = h(n_2) = 2 \cdot n_2 - 1$, while $h(n_1 = 1, n_2 = n_3 \geq 3) = 2 \cdot n_2 - 2$ [6]. Hence, for $n_1 = 2$, it can be easily proved that

$$h(2, n_2, n_3) = 2 \cdot h(1, n_2, n_3) + 1 = \begin{cases} 4 \cdot n_2 - 1 & \text{iff } n_2 < n_3 \\ 4 \cdot n_2 - 3 & \text{iff } n_2 = n_3 \end{cases}$$

(1)
2X3X5 SOLUTION (trivial):
11 lines

NO INTERSECTION

Figure 1. A trivial pattern that completely solves the 2×3×5 points puzzle.

2X5X5 SOLUTION (trivial):
17 lines

Figure 2. Another example of a trivial case: the 2×5×5 points puzzle.

Therefore, the aim of the present paper is to solve the ten aforementioned nontrivial cases where the current upper bound does not match the proved lower bound.


2 Improving the solution of the $n_1 \times n_2 \times n_3$ points problem for $n_3 < 6$

In this complex brain challenge we need to stretch our pattern recognition [7-10] in order to find a plastic strategy that improves the known upper bounds [3-13] for the most interesting cases (such as the nontrivial $n_1 \times n_2 \times n_2$ points problem and the $n_1 \times n_1 \times (n_1 + 1)$ set of puzzles), avoiding those standardized methods which are based on fixed patterns that lead to suboptimal covering paths, as the approaches presented in [2-8-11].

Let $3 \leq n_1 \leq n_2 \leq n_3 \leq 5$, a lower bound of the $n_1 \times n_2 \times n_3$ problem is given by [12]

$$h_l(n_1, n_2, n_3) = \left[\frac{n_1 \cdot (2n_2(n_3+1)-n_1-1)-2}{n_3+n_2-2}\right] - 1$$

(2)

The current best results are listed in Table 1, and a direct proof follows for each nontrivial upper bound shown below.

<table>
<thead>
<tr>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$n_3$</th>
<th>Best Lower Bound ($h_l$)</th>
<th>Best Upper Bound ($h_u$)</th>
<th>Discovered by</th>
<th>Gap ($h_u-h_l$)</th>
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<td>2</td>
<td>3</td>
<td>7</td>
<td>7</td>
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<td>0</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>9</td>
<td>9</td>
<td>trivial</td>
<td>0</td>
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<td>3</td>
<td>3</td>
<td>14</td>
<td>14</td>
<td>Marco Ripà</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(proved in 2013 [14])</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>7</td>
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</tr>
<tr>
<td>2</td>
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<td>4</td>
<td>11</td>
<td>11</td>
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</tr>
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<td>4</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(proved on Jun. 27, 2019 [v1])</td>
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</tr>
</tbody>
</table>
Table 1: Current solutions for the $n_1 \times n_2 \times n_3$ points problem, where $n_1 \leq n_2 \leq n_3 \leq 5$. 

<table>
<thead>
<tr>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$n_3$</th>
<th>Points</th>
<th>Author</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
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<td>4</td>
<td>17</td>
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</tr>
<tr>
<td>4</td>
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<td>4</td>
<td>22</td>
<td>Marco Ripà (NNTDM [13])</td>
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<tr>
<td>2</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>trivial</td>
<td>0</td>
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<td>3</td>
<td>5</td>
<td>11</td>
<td>trivial</td>
<td>0</td>
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<td>15</td>
<td>trivial</td>
<td>0</td>
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<tr>
<td>2</td>
<td>5</td>
<td>5</td>
<td>17</td>
<td>trivial</td>
<td>0</td>
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<tr>
<td>3</td>
<td>3</td>
<td>5</td>
<td>15</td>
<td>Marco Ripà (proved on Jun. 27, 2019 [v1])</td>
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</tr>
<tr>
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<td>18</td>
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<td>27</td>
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<tr>
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<td>3</td>
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</table>
Figures 3 to 12 show the patterns used to solve the $n_1 \times n_2 \times n_3$ puzzle (case by case). In particular, by combining the (2) with the original result shown in figure 4, we obtain a formal proof for the $3 \times 3 \times 4$ points problem.

3X3X3 SOLUTION CONSIDERING TWO DIFFERENT PATHS:

Figure 3. $h_u(3,3,3) = h_l(3,3,3) = 14$. This solution has been proved to be optimal [12-13].
Figure 4. The $3\times3\times4$ puzzle has finally been solved. $h_u = h_l = 15$ and no crossing lines.
Figure 5. Best known upper bound of the 3×4×4 puzzle. $19 = h_u = h_l + 2$.

Figure 6. An original pattern for the 4×4×4 puzzle. $23 = h_u = h_l + 1$ [13].
3X3X5 best upper bound: 16 lines

Figure 7. Best known upper bound of the 3×3×5 puzzle. $16 = h_u = h_l + 1$. 

3x4x5 best upper bound: 20 lines

Figure 8. Best known upper bound of the 3×4×5 puzzle. $20 = h_u = h_l + 2$. 
3x5x5 best upper bound:
24 lines

Figure 9. Best known upper bound of the 3x5x5 puzzle. $24 = h_u = h_l + 4$.

4x4x5 best upper bound:
26 lines

Figure 10. Best known upper bound of the 4x4x5 puzzle. $26 = h_u = h_l + 2$. 
Finally, it is interesting to note that the improved $h_u(n_1, n_2, n_3)$ can lower down the upper bound of the generalized $k$-dimensional puzzle too. As an example, we can apply the aforementioned 3D patterns to the generalized $n_1 \times n_2 \times \ldots \times n_k$ points problem using the simple method described in [12].

Let $k \geq 4$, given $n_k \leq n_{k-1} \leq \cdots \leq n_4 \leq n_1 \leq n_2 \leq n_3$, we can conclude that

$$h_u(n_1, n_2, n_3, \ldots, n_k) = (h_u(n_1, n_2, n_3) + 1) \cdot \prod_{j=4}^{k} n_j - 1$$

(3)
3 Conclusion

In the present paper we have drastically reduced the gap $h_u(n_1, n_2, n_3) - h_1(n_1, n_2, n_3)$ for every previously unsolved puzzle such that $n_3 < 6$. Moreover, we can easily disprove Bencini’s claim that $h_u(3,3,4) = 17 = h_1(3,3,4)$ (see [2], page 7, lines 2-3), since $h_u(3,3,4) = 15 = h_1(3,3,4)$, as shown by combining (2) with the upper bound from figure 4. We do not know if any of the patterns shown in figures 5 to 12 represent optimal solutions, since (by definition) $h_1(n_1, n_2, n_3) \leq h(n_1, n_2, n_3)$. Therefore, some open questions about the $n_1 \times n_2 \times n_3$ points problem remain to be answered, and the research in order to cancel the gap $h_u(n_1, n_2, n_3) - h_1(n_1, n_2, n_3)$, at least for every $n_3 \leq 5$, is not over yet.

References


