Algorithms for the Constrained Longest Common Subsequence Problems

Abdullah N. Arslan[1] and Ömer Eğecioğlu[2*]

[1] Department of Computer Science
University of Vermont
Burlington, VT 05405, USA
e-mail: aarslan@cs.uvm.edu

[2] Department of Computer Science
University of California, Santa Barbara
Santa Barbara, CA 93106, USA
e-mail: omer@cs.ucsb.edu

Abstract. Given strings S_1, S_2, and P, the constrained longest common subsequence problem for S_1 and S_2 with respect to P is to find a longest common subsequence *lcs* of S_1 and S_2 such that P is a subsequence of this *lcs*. We present an algorithm which improves the time complexity of the problem from the previously known $O(rn^2m^2)$ to $O(rnm)$ where r, n, and m are the lengths of P, S_1, and S_2, respectively. As a generalization of this, we extend the definition of the problem so that the *lcs* sought contains a subsequence whose edit distance from P is less than a given parameter d. For the latter problem, we propose an algorithm whose time complexity is $O(drnm)$.

Keywords: Longest common subsequence, constrained subsequence, edit distance, dynamic programming.

1 Introduction

A subsequence of a string S is obtained by deleting zero or more symbols of S. The *longest common subsequence* (*lcs*) problem for two strings is to find a common subsequence in both strings having maximum possible length. The *lcs* problem has many applications, and it has been studied extensively, see for example [1, 4, 2, 3, 5, 7]. The problem has a simple dynamic programming formulation. To compute an *lcs* between two strings of lengths n, and m, we use the *edit graph*. The edit graph is a directed acyclic graph having $(n+1)(m+1)$ lattice points (i, j) for $0 \le i \le n$, and $0 \le j \le m$ as vertices. Vertex $(0, 0)$ appears at the top-left corner, and the vertex (n, m) is at the bottom-right corner of this rectangular grid. To vertex (i, j) there are incoming arcs from its neighbors at $(i-1, j), (i, j-1)$, and $(i-1, j-1)$ which represent, respectively, insert, delete, and either substitute or match operations. The *lcs* calculation counts the number of matches on the paths from vertex $(0, 0)$ to (n, m), and the problem aims to maximize this number. The time complexity lower bound

*Work done in part while on sabbatical at Sabanci University, Istanbul, Turkey during 2003-2004.

for the problem is $\Omega(n^2)$ for $n \geq m$ if the elementary operations are "equal/unequal", and the alphabet size is unrestricted [1]. If the alphabet is fixed the best known time complexity is $O(n^2/\log n)$ when $n = m$ [5]. A survey of practical *lcs* algorithms can be found in [2].

Given strings S_1, S_2, and P, the constrained longest common subsequence problem [6] for S_1 and S_2 with respect to P is to find a longest common subsequence *lcs* of S_1 and S_2 such that P is a subsequence of this *lcs*. For example, for S_1 = `bbaba`, and S_2 = `abbaa`, `bbaa` is an (unrestricted) *lcs* for S_1 and S_2, and `aba` is an *lcs* for S_1 and S_2 with respect to P = `ab`, as shown in Figure 1.

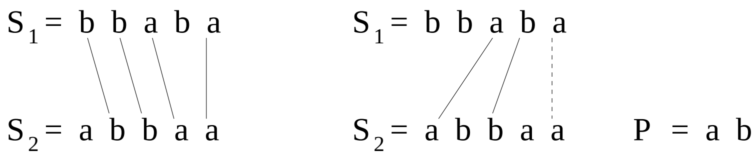

Figure 1: For S_1 = `bbaba`, and S_2 = `abbaa`, the length of an *lcs* is 4 (left). When constrained to contain P = `ab` as a subsequence, the length of an *lcs* drops to 3 (right).

The problem is motivated by practical applications: For example in the computation of the homology of two biological sequences it is important to take into account a common specific or putative structure [6].

Let n, m, r denote the lengths of the strings S_1, S_2, and P, respectively. Tsai [6] gave a dynamic programming formulation for the constrained longest common subsequence problem and a resulting algorithm whose time complexity is $O(rn^2m^2)$. In this paper we present a different dynamic programming formulation with which we improve the time complexity of the problem down to $O(rnm)$. We achieve improved results by changing the order of the dimensions in the formulation. We also extend the definition of the problem so that the *lcs* sought is forced to contain a subsequence whose *edit distance* from P is less than a given positive integer parameter d. For this latter problem we propose an algorithm whose time complexity is $O(drnm)$. Taking $d = 1$ specializes to the original constrained *lcs* problem as this choice of d forces the subsequence to contain P itself. We describe these results in section 2.

2 Algorithms

Let $|S_1| = n$, $|S_2| = m$ with $n \geq m$, and $|P| = r$. Let $S[i]$ denote the ith symbol of string S. Let $S[i..j] = S[i]S[i+1]\cdots S[j]$ be the substring of consecutive letters in S from position i to position j inclusive for $i \leq j$, and the empty string otherwise.

Denote by $L_{i,j,k}$ the length of an *lcs* for $S_1[1..i]$ and $S_2[1..j]$ with respect to $P[1..k]$. This simply means that the common subsequence is constrained to contain P as a subsequence in turn. We calculate the values $L_{i,j,k}$ by a dynamic programming formulation. Then $L_{n,m,r}$ is the length of an *lcs* of S_1 and S_2 containing P as a subsequence.

Theorem 1 *For all* i, j, k, $1 \leq i \leq n$, $1 \leq j \leq m$, $0 \leq k \leq r$, $L_{i,j,k}$ *satisfies*

$$L_{i,j,k} = \max\{L'_{i,j,k},\ L_{i,j-1,k},\ L_{i-1,j,k}\} \tag{1}$$

where

$$L'_{i,j,k} = \max\{L''_{i,j,k},\ L'''_{i,j,k}\} \tag{2}$$

and

$$L''_{i,j,k} = \begin{cases} 1 + L_{i-1,j-1,k-1} & \textit{if } (k = 1 \textit{ or } (k > 1 \textit{ and } L_{i-1,j-1,k-1} > 0)) \\ & \qquad \textit{and } S_1[i] = S_2[j] = P[k] \\ 0 & \textit{otherwise} \end{cases}$$

$$L'''_{i,j,k} = \begin{cases} 1 + L_{i-1,j-1,k} & \textit{if } (k = 0 \textit{ or } L_{i-1,j-1,k} > 0) \textit{ and } S_1[i] = S_2[j] \\ 0 & \textit{otherwise} \end{cases}$$

with boundary conditions $L_{i,0,k} = 0$*,* $L_{0,j,k} = 0$*, for all* i, j, k*,* $0 \leq i \leq n$*,* $0 \leq j \leq m$*,* $0 \leq k \leq r$*.*

Proof We prove the correctness of our formulation by induction on k for all i, j.

We will consider all possible ways of obtaining an *lcs* with respect to $P[1..k]$ at any node i, j. Essentially there are three cases to consider:

1. An *lcs* ending at the node $(i, j-1)$ is extended with the horizontal arc $((i, j-1), (i, j))$ ending at node (i, j),
2. An *lcs* ending at $(i-1, j)$ is extended with the vertical arc $((i-1, j), (i, j))$ ending at node (i, j),
3. An *lcs* ending at node $(i-1, j-1)$ is extended with the diagonal arc $((i-1, j-1), (i, j))$ ending at node (i, j). In this case we distinguish between subcases depending on whether the diagonal arc is a matching for the given strings along with the pattern, or is a matching for the given strings only at the current indices.

The possible *lcs* extensions referred to in items 1 and 2 above are accounted for by $L_{i,j-1,k}$ and $L_{i-1,j,k}$ respectively in the statement of the theorem. The quantities $L''_{i,j,k}$ and $L'''_{i,j,k}$ in the statement of the theorem keep track of the two further possibilities described in item 3.

In the base case: when $k = 0$ (i.e. when P is the empty string) $L''_{i,j,k}$ is identically 0. Therefore $L'_{i,j,k} = L'''_{i,j,k}$ in (2). Since $k = 0$, the conjunction in the definition of $L'''_{i,j,k}$ is always satisfied. We see that putting $L_{i,j} = L_{i,j,0}$, (1) becomes

$$L_{i,j} = \max\{L'_{i,j},\ L_{i,j-1},\ L_{i-1,j}\}$$

where

$$L'_{i,j} = \begin{cases} 1 + L_{i-1,j-1} & \text{if } S_1[i] = S_2[j] \\ 0 & \textit{otherwise} \end{cases}$$

which is the classical dynamic programming formulation for the ordinary *lcs* between S_1 and S_2 [7].

Assume that for $k-1$ $(k \geq 1)$, $L_{i,j,k-1}$ computed by (1) is the length of an *lcs* for $S_1[1..i]$ and $S_2[1..j]$ with respect to $P[1..k-1]$ for all i, j and consider the calculation of $L_{i,j,k}$ when $k > 1$.

We define a *path* at node (i, j) as a simple path in the edit graph which includes at least one matching arc, starts at node $(0, 0)$, and ends at node (i, j). A path with respect to $P[1..k]$ includes matching diagonal arcs ending at a sequence of $k \geq 1$ distinct nodes $(a_1, b_1), (a_2, b_2), \ldots, (a_k, b_k)$ such that for all ℓ, $1 \leq \ell \leq k$, $S_1[a_\ell] = S_2[b_\ell] = P[\ell]$. We define *#match* on a path as the number of matches between the symbols of S_1, and S_2, not necessarily involving symbols in P. An *lcs path* with respect to $P[1..k]$ ending at node (i, j) is a path with respect to $P[1..k]$ ending at node (i, j) with maximum *#match*. Thus $L_{i,j,k}$ is *#match* on an *lcs* path at node (i, j) with respect to $P[1..k]$. Evidently $\#match = \#match(i, j, k)$ is a function of the indices i, j, k. We will omit these parameters when they are clear from the context.

We can extend any *lcs* path with respect to $P[1..k]$ ending at node $(i, j-1)$ with the horizontal arc $((i, j-1), (i, j))$ to obtain a path with respect to $P[1..k]$ ending at node (i, j). Such an extension does not change *#match* on the path, and $L_{i,j,k} \geq L_{i,j-1,k}$.

Similarly we can extend any *lcs* path with respect to $P[1..k]$ ending at node $(i-1, j)$ with the vertical arc $((i-1, j), (i, j))$ to obtain a path with respect to $P[1..k]$ ending at node (i, j). This extension does not change *#match* on the path either, and $L_{i,j,k} \geq L_{i-1,j,k}$. Therefore, $L_{i,j,k} \geq \max\{L_{i,j-1,k},\ L_{i-1,j,k}\}$.

By using a matching arc $((i-1, j-1), (i, j))$, we can obtain paths with respect to $P[1..k]$ at node (i, j) by extending *lcs* paths with either respect to $P[1..k-1]$, or with respect to $P[1..k]$ ending at node $(i-1, j-1)$. These two possibilities are accounted for by $L''_{i,j,k}$ and $L'''_{i,j,k}$ in the dynamic programming formulation, respectively.

First consider *lcs* paths with respect to $P[1..k-1]$ ending at node $(i-1, j-1)$. We will show that $L''_{i,j,k}$ stores the maximum *#match* on paths obtained at node (i, j) by extending these paths.

If $S_1[i] = S_2[j] = P[k]$ then: If $k = 1$ then this is the first time the letter $P[1]$ appears as a matching arc on a path ending at node (i, j) since we are considering *lcs* paths with respect to $P[1..k-1]$ ending at node $(i-1, j-1)$ and $S_1[i] = S_2[j] = P[1]$. Therefore, the *lcs* length relative to $P[1]$ at (i, j) is $L''_{i,j,1} = 1 + L_{i-1,j-1,0}$, which is one more than the length of an ordinary *lcs* between $S_1[1..i-1]$ and $S_2[1..j-1]$. If $k > 1$ and if there is an *lcs* path with respect to $P[1..k-1]$ ending at node $(i-1, j-1)$ (i.e. if $L_{i-1,j-1,k-1} > 0$) then we can extend this path with a new match, and *#match* in the resulting path ending at node (i, j) becomes $L''_{i,j,k} = 1 + L_{i-1,j-1,k-1}$.

Next we consider *lcs* paths with respect to $P[1..k]$ ending at node $(i-1, j-1)$. We will show that $L'''_{i,j,k}$ stores the maximum *#match* on paths obtained at node (i, j) by extending these paths.

If $S_1[i] = S_2[j]$ then: Since the $k = 0$ case is considered earlier in the base case of the induction, we only consider the case when $k > 1$. If there is an *lcs* path with respect to $P[1..k]$ ending at node $(i-1, j-1)$ (i.e. if $L_{i-1,j-1,k} > 0$) then we can extend this path by adding a new match (which does not involve P), and *#match* in the resulting path relative to $P[1..k]$ ending at node (i, j) becomes $L'''_{i,j,k} = 1 + L_{i-1,j-1,k}$.

After setting $L'_{i,j,k} = \max\{L''_{i,j,k},\ L'''_{i,j,k}\}$, the quantity $L'_{i,j,k}$ is equal to the maximum *#match* on paths with respect to $P[1..k]$ ending at node (i, j) ending with the arc $((i-1, j-1), (i, j))$. If there is no such path then $L'_{i,j,k} = 0$. Therefore $L_{i,j,k} \geq \max\{L'_{i,j,k},\ L_{i,j-1,k},\ L_{i-1,j,k}\}$.

From all possible *lcs* paths ending at neighboring nodes of (i, j) we can find their extensions ending at node (i, j), and we can obtain an *lcs* path ending at node (i, j) with respect to $P[1..k]$ for all k. We calculate, and store in $L_{i,j,k}$ such *lcs* lengths. Now consider the structure of an *lcs* path with respect to $P[1..k]$ ending at node (i, j). As

	b	b	a	b	a
a	0	0	1	1	1
b	1	1	1	2	2
b	1	2	2	2	2
a	1	2	3	3	3
a	1	2	3	3	4

$k = 0$

	b	b	a	b	a
a	0	0	1	1	1
b	0	0	1	2	2
b	0	0	1	2	2
a	0	0	3	3	3
a	0	0	3	3	4

$k = 1$

	b	b	a	b	a
a	0	0	0	0	0
b	0	0	0	2	2
b	0	0	0	2	2
a	0	0	0	2	3
a	0	0	0	2	3

$k = 2$

Figure 2: For $S_1 = \texttt{abbaa}, S_2 = \texttt{bbaba}$, and $P = \texttt{ab}$, the tables of values $L_{i,j,k}$ = the length of an *lcs* for $S_1[1..i]$ and $S_2[1..j]$ with respect to $P[1..k]$.

typical in dynamic programming formulations, we consider the possible cases of the last arc on such a path to obtain $L_{i,j,k} \leq \max\{L'_{i,j,k},\ L_{i,j-1,k},\ L_{i-1,j,k}\}$ which proves the theorem. •

Example: Figure 2 shows the contents of the dynamic programming tables for $S_1 =$ bbaba, and $S_2 =$ abbaa, and $P =$ ab for $k = 0, 1, 2$. For $k = 0$, the calculated values are simply the ordinary dynamic programming *lcs* table for S_1 and S_2.

All $L_{i,j,k}$ can be computed in $O(rnm)$ time, using $O(rm)$ space using the formulation in Theorem 1 by noting that we only need rows $i-1$, and i during the calculations at row i. If actual *lcs* is desired then we can carry the *lcs* information for each k along with the calculations. This requires $O(rnm)$ space. By keeping track, on *lcs* for each k, of only the match points (i', j') of $P[u]$ for all u, $1 \leq u \leq r$, the space complexity can be reduced to $O(r^2 m)$. In this case, the *lcs* for $k = r$ needs to be recovered using ordinary *lcs* computations to connect the consecutive match points.
Remark: Space complexity can further be improved by applying a technique used in unconstrained *lcs* computation [3]. We can compute, instead of the entire *lcs* for each k, middle vertex $(n/2, j)$ (assume for simplicity that n is even) at which an *lcs* with respect to $P[1..k]$ passes. This can be done in $O(rm)$ space, and we can compute for all k the *lcs* length $L_{n/2,j,k}$ from vertex $(0, 0)$ to vertex $(n/2, j)$, and *lcs* length from $(n/2, j)$ to (n, m). The latter is done in the reverse edit graph by calculating *lcs* from (n, m) to $(n/2, j)$, hence we denote it by $L^{reverse}_{n/2,j,l}$ for $0 \leq \ell \leq k$. Then for every k,

$$\max_{j, 0 \leq \ell \leq k} L_{n/2,j,l} + L^{reverse}_{n/2,j,k-l}$$

is the *lcs* length for k, and it identifies a middle vertex. After the middle vertex $(n/2, j)$ on *lcs* for every k is found, the problem of finding the *lcs* from $(0, 0)$ to (n, m) can be solved in two parts: find the *lcs* from $(0, 0)$ to $(n/2, j)$, and find the *lcs* from $(n/2, j)$ to (n, m) for all k. These two subproblems can be solved recursively by finding the middle points. This way *lcs* can be obtained using $O(rm)$ space. The time complexity remains $O(rnm)$ because n is halved each time, and the area (in terms of number of vertices) covered in the edit graph is $O(nm)$, and at each vertex the total time spent is $O(r)$.

Next we propose a generalization of the constrained longest common subsequence problem. Given strings S_1, S_2, and P, and a positive integer d the *edit distance* *constrained longest common subsequence* problem for S_1 and S_2 with respect to string P, and distance d is to find a longest common subsequence *lcs* of S_1 and S_2 such that this *lcs* has a subsequence whose edit distance from P is smaller than d. Edit distance between two strings is the minimum number of edit operations required to transform one string to the other. The edit operations are insert, delete, and substitute.

Let $L_{i,j,k,t}$ be the length of an *lcs* for $S_1[1..i]$ and $S_2[1..j]$ such that the common subsequence contains a subsequence whose edit distance from $P[1..k]$ is exactly t.

Example: Suppose $S_1 = \texttt{bbaba}$, $S_2 = \texttt{abbaa}$ and $P = \texttt{ab}$. We have calculated before that the length of an *lcs* for S_1 and S_2 relative to P is 3. Thus $L_{5,5,2,0} = 3$. On the other hand the *lcs* `bbaa` of S_1 and S_2 contains the subsequence `a`, which is edit distance 1 away from P. Therefore $L_{5,5,2,1} = 4$.

We calculate all $L_{i,j,k,t}$ by a dynamic programming formulation. Optimal value of the edit distance constrained *lcs* problem is $\max\limits_{0\le t<d} L_{n,m,r,t}$.

Theorem 2 *For all i, j, k, t, $1 \le i \le n$, $1 \le j \le m$, $0 \le k \le r$, $0 \le t < d$, $L_{i,j,k,t}$ satisfies*

$$L_{i,j,k,t} = \max\{L'_{i,j,k,t},\ L_{i,j-1,k,t},\ L_{i-1,j,k,t}\} \tag{3}$$

where

$$L'_{i,j,k,t} = \max\{L''_{i,j,k,t},\ L'''_{i,j,k,t},\ L''''_{i,j,k,t}\} \tag{4}$$

where

$$L''_{i,j,k,t} = \begin{cases} 1 + L_{i-1,j-1,k-1,t} & \text{if } ((k=1 \text{ and } t=0) \text{ or} \\ & (k>1 \text{ and } L_{i-1,j-1,k-1,t} > 0)) \\ & \qquad \text{and } S_1[i] = S_2[j] = P[k] \\ 0 & \text{otherwise} \end{cases}$$

$$L'''_{i,j,k,t} = \begin{cases} 1 + L_{i-1,j-1,0,0} & \text{if } (k=0 \text{ and } t=1) \text{ and } S_1[i] = S_2[j] \\ 1 + L_{i-1,j-1,k,t} & \text{else if } (k=0 \text{ or } L_{i-1,j-1,k,t} > 0) \\ & \qquad \text{and } S_1[i] = S_2[j] \\ 0 & \text{otherwise} \end{cases}$$

$$L''''_{i,j,k,t} = \max\{D_{i,j,k,t},\ X_{i,j,k,t},\ I_{i,j,k,t}\} \tag{5}$$

where

$$\begin{aligned} D_{i,j,k,t} &= \begin{cases} L_{i,j,k-1,t-1} & \text{if } t \ge 1 \\ 0 & \text{otherwise} \end{cases} \\ X_{i,j,k,t} &= \begin{cases} L_{i,j,k-1,t-1} & \text{if } t \ge 1 \text{ and } S_1[i] = S_2[j] \\ 0 & \text{otherwise} \end{cases} \\ I_{i,j,k,t} &= \begin{cases} L_{i,j,k,t-1} & \text{if } t \ge 1 \text{ and } S_1[i] = S_2[j] \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

with boundary conditions $L_{i,0,k,0} = 0$, $L_{0,j,k,0} = 0$, for all i, j, k, $0 \le i \le n$, $0 \le j \le m$, $0 \le k \le r$.

Proof We claim that $L_{i,j,k,t}$ is the optimum length for any lcs for $S_1[1..i]$ and $S_2[1..j]$ such that the lcs contains a subsequence whose edit distance is t from $P[1..k]$. We prove the correctness of our formulation by induction on t for all i, j, k.

In the base case: when $t = 0$ the formulation becomes the same formulation as in Theorem 1, since now the lcs is required to contain P itself as a subsequence. Therefore, the correctness of this case follows from Theorem 1.

Assume that for $t - 1$ ($t \geq 1$), for all i, j, k, $L_{i,j,k,t-1}$ is the optimum length for any lcs for $S_1[1..i]$ and $S_2[1..j]$ such that the lcs contains a subsequence whose edit distance is t from $P[1..k]$. Consider the calculation of $L_{i,j,k,t}$ for all i, j, k when $t > 1$.

Our formulation uses the following observation: Let cs be a subsequence of an lcs of S_1 and S_2. The minimum edit distance between cs and P can be calculated using insert, delete, and substitute operations in P, and using no operations in cs. To see this consider the edit operations between the symbols in cs, and in P. If an edit distance calculation deletes a symbol s in cs, we can instead insert the symbol s in P; if a minimum edit distance calculation inserts a symbol s in cs, we can instead delete the symbol s in P; and if a minimum edit distance calculation substitutes a symbol s' for s in cs, we can instead substitute a symbol s for s' in P to obtain the same edit distance.

We define an *edit path* at node (i, j) at distance t from $P[1..k]$ as a simple path from node $(0, 0)$ to node (i, j), which includes a sequence of $l \geq 1$ distinct nodes $(a_1, b_1), (a_2, b_2), \cdots, (a_l, b_l)$ such that the edit distance between the string $S_1[a_1]S_2[a_2] \ldots S_1[a_l]$ ($= S_2[b_1]\ S_2[b_2] \ldots S_2[b_l]$), and $P[1..k]$ is exactly t. We define $\#match$ on a given edit path to node (i, j) as the number of matching diagonal arcs on the path between the symbols in $S_1[1..i]$, and the symbols in $S_2[1..j]$, not necessarily involving matches in P. An optimal edit path at node (i, j) at distance t from $P[1..k]$ is an edit path at node (i, j) at distance t from $P[1..k]$ with maximum $\#match$. Thus $L_{i,j,k,t}$ is $\#match$ on an optimal edit path at node (i, j) at distance t from $P[1..k]$. In this case, $\#match = \#match(i, j, k, t)$ is a function of the indices i, j, k, t, but we omit these parameters when they are clear from the context.

We can extend any optimal edit path at node $(i, j-1)$ at distance t from $P[1..k]$ with the horizontal arc $((i, j-1), (i, j))$ to obtain an edit path at node (i, j) at distance t from $P[1..k]$. Such an extension does not change $\#match$ on the resulting edit path, and $L_{i,j,k,t} \geq L_{i,j-1,k,t}$.

Similarly we can extend any optimal edit path at node $(i-1, j)$ at distance t from $P[1..k]$ with the vertical arc $((i-1, j), (i, j))$ to obtain an edit path at node (i, j) at distance t from $P[1..k]$. This extension does not change $\#match$ on the resulting edit path, and $L_{i,j,k,t} \geq L_{i-1,j,k,t}$. Therefore, $L_{i,j,k,t} \geq \max\{L_{i,j-1,k,t},\ L_{i-1,j,k,t}\}$.

By using a matching arc $((i-1, j-1), (i, j))$, we can obtain edit paths at node (i, j) at distance t from $P[1..k]$ by extending optimal edit paths at node $(i-1, j-1)$ at distance $t-1$, or t from $P[1..k-1]$, or $P[1..k]$.

First consider optimal edit paths at node $(i-1, j-1)$ at distance t from $P[1..k-1]$. We will show that $L''_{i,j,k,t}$ stores the maximum $\#match$ obtained at node (i, j) by extending these edit paths.

If $S_1[i] = S_2[j] = P[k]$ then: We do not need to consider the case when $k = 1$ and $t = 0$ since $t = 0$ case is considered in the base case of the induction. If $k > 1$ and if there is an optimal edit path at node (i, j) at distance t from $P[1..k]$ (i.e. if

$L_{i-1,j-1,k-1,t} > 0$) then we can extend this edit path with a new match, and $\#match$ on the resulting edit path at node (i,j) at distance t from $P[1..k]$ becomes $L''_{i,j,k,t} = 1 + L_{i-1,j-1,k-1,t}$.

Next we consider optimal edit paths at node $(i-1, j-1)$ at distance t from $P[1..k]$. We will show that $L'''_{i,j,k,t}$ stores the maximum $\#match$ obtained at node (i,j) by extending these edit paths.

If $S_1[i] = S_2[j]$ then: If $k = 0$ and $t = 1$ then: We can extend an *lcs* path ending at node $(i-1, j-1)$ with respect to $P[1..k]$ with a match. In this case, $\#match$ in the resulting edit path is one more than $L_{i-1,j-1,0,0}$. Therefore, $L'''_{i,j,0,1} = 1 + L_{i-1,j-1,0,0}$. Otherwise if $k = 0$ then we can extend an optimal edit path at node $(i-1, j-1)$ at distance t from $P[1..k]$ with a match, and $\#match$ on the resulting edit path is $L'''_{i,j,k,t} = 1 + L_{i-1,j-1,k,t}$.

Any edit path at node (i,j) at distance $t-1$ from $P[1..k-1]$, or $P[1..k]$ can be modified by applying an edit operation in P. We can modify an edit path at node (i,j) at distance $t-1$ from $P[1..k-1]$ by deleting $P[k]$. Then on the resulting edit path $\#match$ remains the same, and the distance increases by 1. Therefore, we set $D_{i,j,k,t} = L_{i,j,k-1,t-1}$, and take it into account in $L''''_{i,j,k,t}$. We can modify an edit path at node (i,j) at distance $t-1$ from $P[1..k-1]$ by substituting $S_1[i] = S_2[j]$ for $P[k]$. Then on the resulting edit path $\#match$ remains the same, and the distance increases by 1. Therefore, we set $X_{i,j,k,t} = L_{i,j,k-1,t-1}$ if $S_1[i] = S_2[j]$, and take it into account in $L''''_{i,j,k,t}$. We can also modify an edit path at node (i,j) at distance $t-1$ from $P[1..k]$ by inserting $S_1[i] = S_2[j]$ in P after position k. Then on the resulting edit path $\#match$ remains the same, and the distance increases by 1. Therefore, we set $I_{i,j,k,t} = L_{i,j,k,t-1}$ if $S_1[i] = S_2[j]$, and take it into account in $L''''_{i,j,k,t}$. Combining all these $L''''_{i,j,k,t} = \max\{D_{i,j,k,t},\ X_{i,j,k,t},\ I_{i,j,k,t}\}$.

After setting $L'_{i,j,k,t} = \max\{L''_{i,j,k,t},\ L'''_{i,j,k,t},\ L''''_{i,j,k,t}\}$, $L'_{i,j,k,t}$ stores the maximum $\#match$ on edit paths at node (i,j) at distance t from $P[1..k]$ whose last arc is $((i-1, j-1), (i,j))$. If there is no such edit path then $L'_{i,j,k,t} = 0$.

From all possible optimal edit paths at neighboring nodes of (i,j) we can obtain their extensions ending at node (i,j), and we can find an optimal edit path at node (i,j) at distance t from $P[1..k]$ for all k, t. We calculate, and store in $L_{i,j,k,t}$ maximum $\#match$ in such optimal edit paths. Considering the possible cases of the last arc on an optimal edit path at node (i,j) at distance t from $P[1..k]$ we also have $L_{i,j,k,t} \leq \max\{L'_{i,j,k,t},\ L_{i,j-1,k,t},\ L_{i-1,j,k,t}\}$. This concludes the proof of the theorem. •

All $L_{n,m,r,t}$ for $t = 0, 1, \cdots, d-1$ can be computed in $O(drnm)$ time, and using $O(drm)$ space using the formulation in Theorem 2 by noting that we only need rows $i-1$, and i during the calculations at row i. If an actual optimal edit path is desired then we can carry the edit path information for every k and t along with the calculations. This requires $O(drnm)$ space since edit paths can be of length $O(n)$.

If we store match points (where the symbols of S_1, S_2, and P match) on these edit paths then we can reduce the required space to $O(dr^2m)$. In this case, the optimal edit path of the problem needs to be recovered using ordinary *lcs* computations to connect the consecutive match points.

Remark: Space complexity can further be improved by using the technique we used in our first algorithm. We can compute, instead of the entire edit path for each k, and t, a middle vertex $(n/2, j)$ (assume for simplicity that n is even) at which an edit path at distance t from $P[1..k]$ passes. This can be done in $O(drm)$ space, and we can compute for all k, and t, $\#match$ $L_{n/2,j,l,u}$ on optimal edit path from vertex $(0,0)$ to vertex $(n/2,j)$, and $\#match$ on optimal edit path from $(n/2,j)$ to (n,m) where $0 \le \ell \le k$, and $0 \le u \le t$. The latter, denoted by $L^{reverse}_{n/2,j,k-l,t-u}$, can be calculated in the reverse edit graph. Then for all k,t,

$$\max_{j,0\le\ell\le k,0\le u\le t} L_{n/2,j,l,u} + L^{reverse}_{n/2,j,k-l,t-u}$$

is the optimum $\#match$ for k,t, and it identifies a middle vertex. After the middle vertex $(n/2,j)$ on optimal edit path for every k,t is found, the problem of finding an optimal edit path from $(0,0)$ to (n,m) can be solved in two parts: find an optimal edit path from $(0,0)$ to $(n/2,j)$, and find and optimal edit path from $(n/2,j)$ to (n,m) for all k,t. These two subproblems can be solved recursively. As a results an optimal edit path can be obtained using $O(drm)$ space. The time complexity remains $O(rnm)$ because n is halved each time, and the area (in terms of number of vertices) covered in the edit graph is $O(nm)$, and at each vertex the total time spent is $O(dr)$.

3 Conclusion

We have improved the time complexity of the constrained *lcs* problem from $O(rn^2m^2)$ to $O(rnm)$ where n, and m are the lengths of the given strings, and r is the pattern length. This improvement is achieved by a dynamic programming formulation which is different from what was proposed in [6]. In our formulation, the dimensions are ordered differently. We also extended the problem definition to use edit distances, and presented an $O(drnm)$ time algorithm for the resulting edit distance constrained *lcs* problem.

References

[1] A.V. Aho, D.S. Hirschberg, and J.D. Ullman. Bounds on the complexity of the longest common subsequence problem. *J. ACM*, 23(1):1–12, 1976.

[2] L. Bergroth, H. Hakonen, and T. Raita. A survey of longest common subsequence algorithms. *SPIRE, A Coruna, Spain*, pp. 39–48, 2000.

[3] D.S. Hirschberg. A linear space algorithm for computing maximal common subsequences. *Communications of ACM*, 18:341–343, 1975.

[4] D.S. Hirschberg. Algorithms for the longest common subsequence problem. *J. ACM*, 24:664–675, 1977.

[5] W.J. Masek and M.S. Paterson. A faster algorithm computing string edit distances. *J. Comput. System Sci.*, 20:18–31, 1980.

[6] Yin-Te Tsai. The constrained common sequence problem. *Information Processing Letters*, 88:173–176, 2003.

[7] R.A. Wagner and M.J. Fisher. The string-to-string correction problem. *J. ACM*, 21:168–173, 1974.