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# Modeling Plant Variations through 3D Interactive Sketches

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**Abstract**

*Modeling realistic looking plants is still a complex problem requiring specification of plant structure, geometry and surface characteristics. Modeling a collection of plants is more problematic especially since each plant is slightly different. Altering the shape of branches and stems is one of the most dramatic and natural methods of creating differing instances of the same plant type. We present a sketch-based interface for modeling plant variations through specification of branch and stem shape. Our system is based on interaction with the 3D Tractus: a new physical interface we developed to support direct 3D sketching. The 3D strokes from the 3D Tractus are used as input to a biologically-based modeling method that mimics natural growth variation factors of real plants.*

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling: Modeling packages

## 1. Introduction

In nature no two instances of a single plant type are exactly the same. This fact must be preserved when trying to model a large collection of the same type of plant. As computer generated scenes become more complex, the desire to include many plants in a scene increases. The most profound difference between plant instances is often the shape of the branches and stems of the plant.

To model a collection of differing plant instances it is desirable to interactively specify and control branch and stem shape. Other modeling systems allow the user to control a variety of parameters, which often reflect features of the geometry [OHKK03] rather than structure. Some previous work has interactively specified structural components such as branch and stem shape, but are restricted to specifying these shapes in a 2D domain [LD99, OOI05] and often assume certain constraints (i.e. clamping to the surface, constant curvature) in order to create a 3D curve.

Interactively specifying plant shape parallels 3D curve design [CMZ*99, CHZ00]. The most direct method of defining 3D curves is to draw them; however drawing 3D curves and strokes is problematic when working in a 2D domain. Sketch-based modeling has recently been used for creating plant models [IITS04, IOOI05, OI03, OOI05]. All these methods rely on certain assumptions or techniques to infer the 3D shape or model from the 2D strokes.

We present a system for creating a variety of plant instances from a single plant model using direct 3D strokes (Figure 1). We use a physical 3D drawing-board interface for sketching stem and branch shapes in 3D. The sketched stems and branches are directly employed as realistic variations to the original plant model [SFS05]. Our main contribution is the unique system which combines the 3D drawing-board with creating plant model variation for creating plant collections. Our technique includes a unique method of creating and editing strokes as well as associating them with a base model. The result is an intuitive, direct, and quick method for creating a variety of plants from a single model, to facilitate creating large plant model collections.

## 2. Related Work

Modeling of plants has been addressed by the computer graphics community for decades [AK84, PL90]. Since our focus is to create variations in plant model instances, we overview previous work that permits interactive editing of models to create different plant model instances rather than creation of models. Also, since we use a 3D interface in a sketch-based paradigm, we overview work in this context.

### 2.1. Interactive Plant Design

With increases in computational power, interactive modeling of complex models such as plants has recently become possible. As Lintermann and Deussen [LD99] describe, many plant modeling approaches can be classified as either biologically motivated to simulate natural plant development, or to generate visually correct shape. Interactive modeling applications belong to the latter and is likewise our focus.

Interactive plant modeling techniques target three aspects: data, means and method of interaction. The data is typically surface geometry [OHKK03], a structural representation [PBPS99, BPF*03], or some combination of these two [LD99]. The interaction means is traditionally manipulation of the 3D model in a 2D view plane while selecting various joints or plant aspects using a 2D pointer (e.g. mouse) or a 3D magnetic tracker [OHKK03]. The interaction method has involved applying editing operations to various amounts or levels of plant structure simultaneously to reduce tedium with highly complex models. Some techniques use the spatial arrangement to select components or aspects of the plant within a particular region [OHKK03], some use silhouettes for bounding regions [BPF*03], some craft the model's parameters to allow for multi-resolution editing through parameter alteration [LD99] and others use the model's structural representation [LD99, BPF*03].

The goal is often the control of shape. To improve realism some techniques assist the user by imposing physical constraints given the user's input such as the inverse-kinematic approach of Power et al. [PBPS99], or the use of transformation or developmental rules such as growth of buds or leaves of Onishi et al. [OHKK03]. Lintermann and Duessen [LD99] provide a few options to control overall shape including functional modeling, tropisms or freeform deformation, but their method seems more difficult when specifying individual branch and stem shape. Boudon et al. [BPF*03] allow specification of shape through editing of 2D curves by manipulating control points in 3D space to represent axes of structures.

While these editing methods as well as various commercial procedural methods for creating plants [IDV05, OC05] provide a means of creating variation by specifically interacting with the parameters or geometry of the model, individually editing the many components of the model numerous times to create a large collection of these varied models is too tedious. A common method to quickly introduce variations involves randomly [OC05] or systematically varying parameters [LD99, Xfr05], however these methods are not controllable and are often too sensitive.

Our objective is to make use of the skeletal representation for multi-resolution editing while providing a means of intuitive direct 3D manipulation. Similar to Power et al. [PBPS99] and Onishi et al. [OHKK03] we use a L-system to represent the plant structure. However, we do not constrain the user by physical parameters [PBPS99] and do not force the user to manipulate individual controls [BPF*03, LD99] or joints to communicate transformations [OHKK03], but rather the user simply draws the intended branch and stem manipulations directly in 3D.

Furthermore, since our goal is create variation for a collection of plants the sketch-base interaction provides a natural means of creating variation in the same way artists create a 'likeness' of a plant. A painting or drawing of a plant can be easily recognized as a particular plant, but is rarely if ever an exact representation of the real plant.

In addition to using sketch input for variation we use the sketched information as input to the procedural method of Streit et al. [SFS05] to add biological variation that occurs naturally through development. With the combined technique we can create user controlled differences in the plant model, particularly in the shape of branches and stems with an underlying biology-based variation.

### 2.2. Three-Dimensional Interfaces

Sach's et al. [SRS91] 3-Draw system and other free space devices using six degrees of freedom (DOF) [BBMP97, HRPGK94, PTW98] are early examples of pioneering 3D interfaces for sketching, manipulation and drawing. These systems require the use of a virtual reality environment, typically including head mounted displays (HMD), stereo shutter glasses, and tethered 6 DOF trackers. All of this complex and usually expensive equipment can be seen as a disadvantage, and designers who are used to working on physical surfaces often find these systems difficult to use.

Both the CAT and Interaction Table [HGRT03, HG02] use a physical touch sensitive surface to provide the user 6 DOF. However, both interfaces rely on physical pressure instead of movement to navigate a virtual world. ArtNova and inTouch [FOL02, GEL00] use SensAble's PHANTOM Haptic device [ST05] to allow the user to directly interact with virtual 3D objects. The PHANTOM provides force-feedback directly to the user's arm or hand.

The Boom Chameleon [TFK*02] lets the user interact with a touch sensitive display mounted on a position sensitive arm. The display acts as a window into the virtual space, and the user can annotate and interact with the 3D scene. To our knowledge this apparatus is neither simple, nor inexpensive and has not been used for 3D drawing.

### 2.3. Sketch-based Plant Modeling Interfaces

Recently, systems have been developed to create and manipulate plant models through a sketch-based interface. Ijiri et al. [IITS04, IOOI05] introduce a methodology for modeling flowers using floral diagrams and inflorescence. Their geometry editor uses two sketched cross-sectional strokes to shape a flat leaf into a curved one. An additional sketched stroke defines the central axis of a selected inflorescence. From the 2D free-form strokes they create 3D geometry by adding depth to the strokes using the assumption of constant

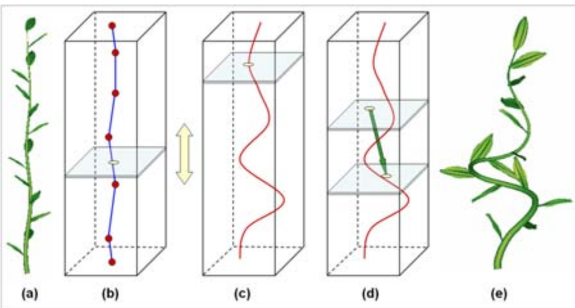


**Figure 1:** *Given a 3D plant model (a) and its extracted skeleton (b) the user selects segments (blue) from the skeleton (b) and sketches corresponding strokes (c) using the* 3D Tractus. *These strokes together with macro sketch-based motion indicators for overall growth direction (d) are used to control growth variation (e).*

curvature. Other parameters and a flower diagram help define various model characteristics.

Okabe et al. [OI03, OOI05] present a method for modeling trees from sketches. Their technique generates 3D geometry from a 2D sketch by assuming that botanical trees tend to maximize the distance between branches and that most users tend to draw branches that extend sideways rather than into or out of the drawing plane. They introduce three editing modes to assist the user in creating repetitive arrangements, rather than specifying rules or parameters to create the model. As the authors state, currently their system is limited to single trees. Creation of other types of plants and similar trees for forming collections of plants is not possible. Our focus is the creation of varied models for the purposes of generating collections of a wide range of plant models.

## 3. System Overview and Interface

Our system is based on a 3D interface which permits users to draw strokes directly in 3D space. As shown in Figure 1, the user selects a base plant model, to which they would like to add variations. Following the system extracts the skeleton of this model. We currently use an L-system description of the plant model and a wire-frame interpretation of the L-system string for the skeleton. The user then sketches strokes directly in 3D using the 3D Tractus [LSSS06], as shown in Figure 2. These strokes indicate how the branches of the base model's skeleton should be varied. These strokes are used as input to a procedural method which adds variation to the model through a growth-based simulation.

The 3D Tractus is a simple physical interface that allows the user to draw on a flat surface (such as a tablet PC) while moving the surface up and down, as shown in Figure 2. The 3D Tractus uses a simple and inexpensive string-potentiometer to measure the interaction surface height. Following, all the user's surface interactions are mapped in 3D, and the system can display related 3D feedback to the user

**Figure 2:** *A user interacting with the* 3D Tractus.

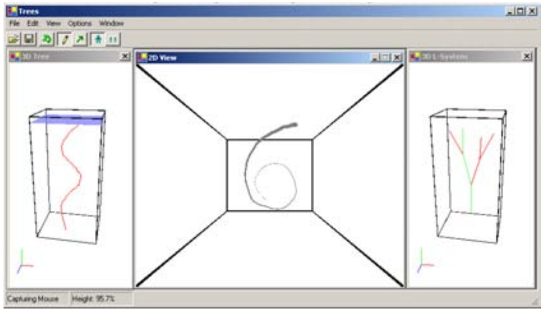


**Figure 3:** *A screenshot showing a spiralling stroke (left and center) and the plant skeleton (right).*

in real time according to the surface height [LSSS06]. The result is that the user can generate 3D curves directly, without having to resort to GUI widgets as in other 2D interfaces such as commercially available Maya$^{TM}$ or 3DS Max$^{TM}$.

The software presented to the user is controlled exclusively by a pointer, facilitating sketching without interruptions or need to resort to the keyboard. There are three main areas of the application that the user sees. The first is the tree skeleton, which shows the L-system in a 3D view that can be rotated, as shown on the right in Figure 3. The user selects branches that they want to add variations to from this view. In another window, the user employs the 3D Tractus to draw the 3D curve that describes the branches that they selected, as shown in the center. Finally, the user sees the curves that they have drawn in a 3D view shown on the left.

## 4. Creating Variation

Variation is added to the base model through alteration of branch and stem shape. This can have a profound affect on the look of the plant without changing any other attributes of the model. Variation can be added to the branches and stems in three forms: intentional artistic, unintentional artistic and growth-based [SFS05]. Direct inputting of variations using 3D Tractus sketches employs the artistic variation form. By drawing the shape of the branches, variation can be deliberately introduced through definitive alterations in the branch orientation and direction as well as unintentional imprecision due to hand gestures in the drawing of the stroke. Using sketched strokes in free-form drawing as a source of variations, results in better approximations of the process of traditional illustration production.

Mapping the user-drawn strokes to the original model is not an easy problem and parallels graph-matching problems. Without imposing some ordering on the drawing the complexity of the matching problem grows exponentially with each stroke drawn. To avoid imposing restrictions on drawing order and to improve interaction even with complex models, we chose to have the user first indicate to which branch or branch component they are associating a stroke through selection. Of course selecting each and every branch and associating a stroke with it can be tedious with overly complex models, thus a means of propagating the stroke to utilize the natural repetition in botanical models is used. The stroke propagation facilitates hierarchical editing of the model to assist in both control over fine details and quick, efficient definition of models. As the user associates strokes a view of the model is updated and the user can choose to render the complete geometry of the model at any stage.

### 4.1. Plant Skeleton and Selection

To generate variation, the user starts with a base plant skeleton which is generated from geometric transformations of an L-system [PL90] string. Hierarchical information is computed from the set of line segments representing the skeleton by forming joints at common endpoints. This information is constructed from root to tip such that any segments (herein branches) that stem from a common branch are its' children resulting in an n-ary tree (Figure 4). The user then selects branches from the n-ary tree and adds variation by associating drawn strokes with the selected branches.

A painter's algorithm [FvDFH96] is used for skeletal segment selection. The user draws a 2D stroke on top of the tree skeleton, displayed in 3D, and any branches that lie under the stroke are selected. This lets the user directly select the desired branches. However, most interesting tree skeletons have a large number of branches, many of them small, meaning that simply selecting branches that lie under the stroke may erroneously select many unwanted branches.

Smart decisions about the user's intended selection are made using the hierarchical information. We restrict selection of branches to one direction, descending down the n-tree, for example, you cannot select a child branch and then select its parent. Although restrictive, it is common practice to draw trees from the main trunk outward to more minor branches [Mal99].

Each branch segment can transition between three states: unselected, selected or undetermined as shown in Figure 5. The undetermined state is similar in appearance to the unselected state. As the user draws the selection stroke, selected

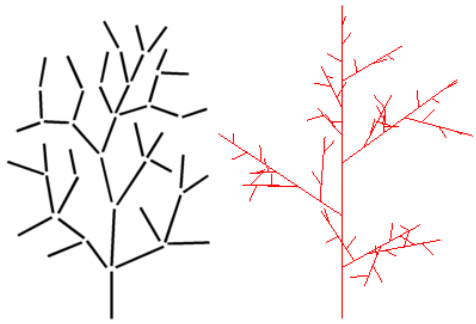

**Figure 4:** ***Left:*** *Conceptual n-ary tree where child and parent associations occur at joint locations* ***Right:*** *3D n-ary tree from skeleton of base model.*

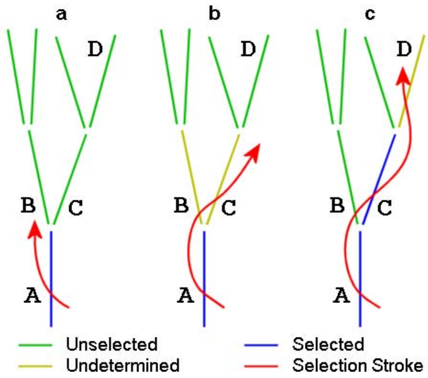


**Figure 5:** *Selection of branches A-D; Coloured segments show selected, unselected, and undetermined branches with progress of curved selection stroke (a–c).*

branches are drawn in a different color to indicate that they are selected. Branches can be in an undetermined state when the system cannot decisively determine if the segment was intended for selection. Like in a linked list, only a sequential path of branches may be selected.

Assume the user starts selection; all branches are unselected (Figure 5). The user initially draws a stroke over top of some branch A. No branches have previous been selected or marked undetermined, so branch A is immediately selected. The user continues the stroke upward and accidentally draws on top of one of A's children; the child branch B is temporarily marked as undetermined. Continuing the stroke upward, the user intentionally draws over another one of A's children and branch C is also temporarily marked as undetermined. Continuing the stroke upward, the user intentionally draws over another one of A's children and the branch, C, is also temporarily marked as undetermined. The two branches B and C are marked undetermined because the system is unsure which branch the user really wanted to select.

As the stroke is drawn further upward, it is drawn over top of a branch, D, that is one of C's children (A's grand-

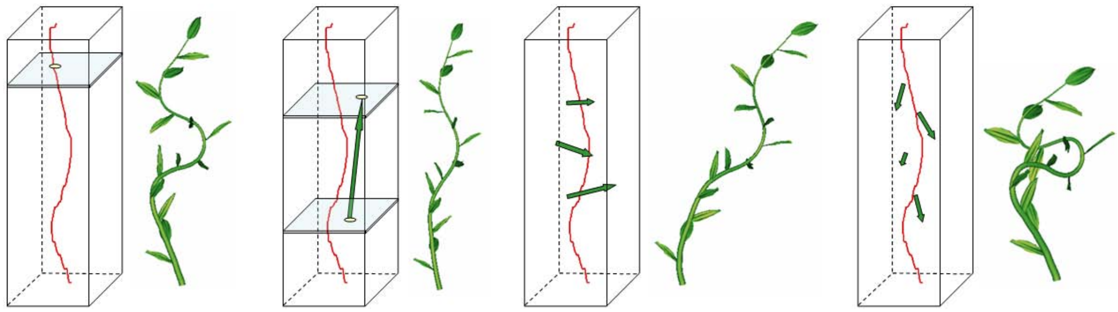

**Figure 6:** *Motion indicators representing dominant environmental factors which affect overall stem shape.*

child). This additional information helps to resolve our previous undetermined state. Since the user is now selecting C's child, the system determines that the user did not intend to select branch B but intended to select branch C. At this point, branch C is marked selected, branch B is marked as unselected, and branch D is marked as undetermined. The selection process continues as before until the user finishes the selection action (finishing the stroke and raising the stylus). At this point any remaining undetermined branches will become selected. Conversely, had the user drawn over top of B's children, the system would have unselected C.

### 4.2. Sketching Strokes

After selecting which branches will have variations added, users draw the 3D curves that defines the path of branch growth. These 3D curves are generated by sketching on top of the interaction surface while moving the 3D Tractus up or down. The tablet PC placed on top of the 3D Tractus behaves as a 'window' that allows the user to view the volume that they may draw in. Because we are viewing 3D curves on a 2D display, users must be given additional information that intuitively conveys the depth of these lines, or distance from the viewing window. Several approaches were designed, but we found that the most intuitive and clear communication of depth information is the use of line thickness when viewed with a perspective projection, as shown in Figure 3 (versus orthographic projection) [LSSS06].

### 4.3. Stroke Propagation for Multi-resolution Editing

As mentioned, the most interesting tree skeletons consist of a large number of branches, some of which may be very short. It would not make sense for the user to give the same amount of attention to the small leaf branches as they do to the main trunk or other large branches. At the same time, having variation in the small branches is still essential to generate realistic looking plants. We propose a feature where the user may control the resolution of the branches that the curve is applied to with two modes.

The first mode applies the curve only to the selected branches. However, this is insufficient for editing many branches quickly, especially small ones. The other mode handles the problem of defining variation for many small branches by applying the same curve to every single branch that is a descendant of the selected branches, all the way down to the leaf branches. The user may wish to combine both modes, so that all the descendants and the selected branches themselves are associated with a drawn stroke. This propagated editing can be over-ridden by simply selecting the desired branches and drawing the stroke to be associated with these branches. This flexibility allows the user to add variation to small branches without spending a lot of time drawing, but still allows details to be added if required. Multi-resolution editing can be applied to many branches whose shape is intended to be similar. However if the collection of associated branches includes branches of varying scales, due to re-sampling of the stroke the shape of very small branches may not always appear visually similar making the tree look more realistic.

### 4.4. Sketching Motion Indicators

In traditional sketching, artists use light line strokes to indicate aspects such as wind, sun, or rain. For example, an image with many long vertical lines, would indicate it was raining, and particularly hard. If the lines were shorter, it would convey a feeling of lighter rain. We use the same principle in our system. Influences such as wind, water, or sunlight may all be added through the creation of motion indicators. Motion indicators are sketch-based vectors which are added together to skew the overall growth of the plant. They are created by drawing and moving the 3D Tractus up and down, just like curves, except that only the start and end points are used. If the user wishes to add wind, so that the plant will be skewed to one side, he/she would draw a series of motion indicators in a horizontal direction. Sunlight may be added by drawing long upward motion indicators. Rain may push the plant down slightly, so downward motion indicators would be drawn. See Figure 6 for motion indicator examples.

### 4.5. Further Variation with a Biological Basis

Once the drawn strokes and motion indicators are associated with the base model, this determines the predefined growth

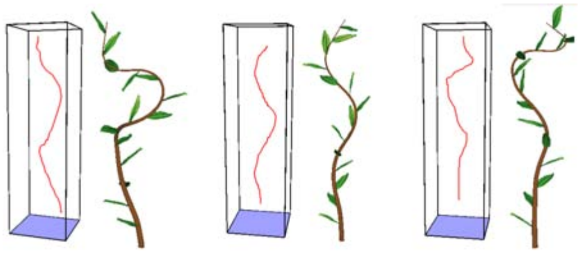

**Figure 7:** *Examples showing variations of original plant model (leftmost image) from user drawn 3D strokes.*

direction and dominant influence respectively, in the growth simulation [SFS05]. The simulation incorporates numerous environmental factors affecting plant growth as random influences. These influences with the user data indirectly determine growth direction throughout the growth simulation. As the plant grows, a difference between the current and predefined (user's strokes) growth directions is determined. This difference is used to add further subtle, biological variation in branch and stem shape beyond what is specified by the user's strokes. Since the strokes are aligned with the branches, the branch topology and orientation remain consistent with the base model. This approach facilitates generating a large number of plants which have identical overall controlled branch and stem shape as defined by the user's stroke association with the base model, but with subtle variation. Section 5 shows example results.

## 5. Results and Discussion

Figure 7 shows examples of strokes in 3D space with corresponding resulting plants. Examples of plant collections generated by our method are shown in Figures 8 and 10. Our method facilitates quick creation of a collection of similar plants though direct sketch-based variation of branch and stem shape. Our approach maintains the branch location and orientation defined by the base-model, so that the resulting branch arrangement does not differ from the desired model. Due to variations in stroke path (Figure 7) and growth simulation (Figures 8 to 10) the resulting shape of the branch and direction of the tip can differ. Also, the overall direction of branch growth can be altered by adding indicators representing environmental factors as outlined in Section 4.4. Our selection method (Section 4.1) allows users to quickly and efficiently associate strokes with branches to create variation even with more complex models. Figure 9 shows an example with four branching levels. Furthermore, with our system, users have true 3D interaction for drawing the strokes.

We performed a preliminary small-scale user study to gather feedback about our system's usability. We recruited three computer science graduate students, two with strong art backgrounds. The participants were first informed about the purpose of our system and shown a brief demo. Each

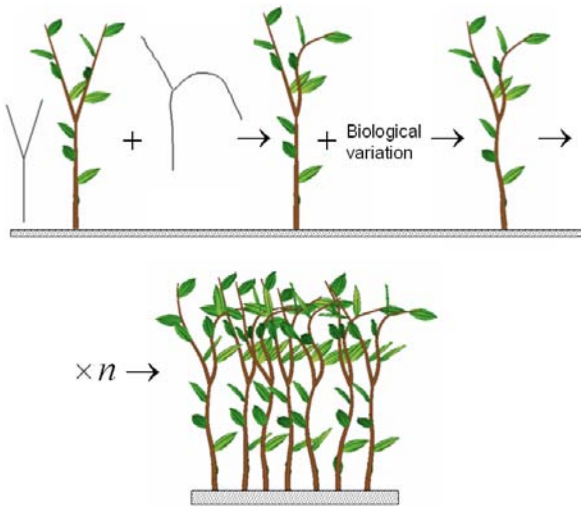


**Figure 8:** *Sketch-based variation of branching structures. **Top Row:**Original model and skeleton with stroke and biological variation **Bottom row:** collection of seven instances.*

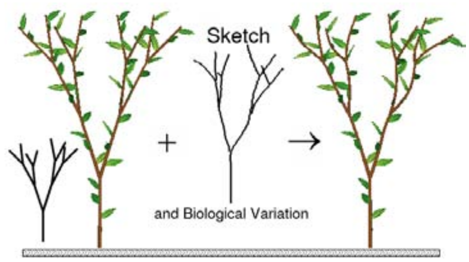


**Figure 9:** *Figure 8's model with more branching levels.*

participant went through a training session using a simple L-system model and then got to use the application freely with two different and more elaborate L-system models. Each experiment took about 40 minutes. The experiment was evaluated by a simple qualitative, direct observation method using a video camera for documenting the sessions and the participants' interaction and feedback, and a structured interview for collecting comments at the end of each experiment.

All the participants enjoyed using the 3D Tractus-based application and commented that since every curve they drew generated a different looking plant it was easy and intuitive to generate random plants. All participants were able to effectively use the motion indicators and simulate wind and sun effects quickly and accurately. Selection was found to be very effective and assisted the participants when attempting to refer to branches in a large plant. Participants commented that the system was able to correctly resolve which branch they wanted to select, allowing them to choose branches quickly and with accuracy.

While our system was generally well received, participants indicated the desire for more control of the plant's

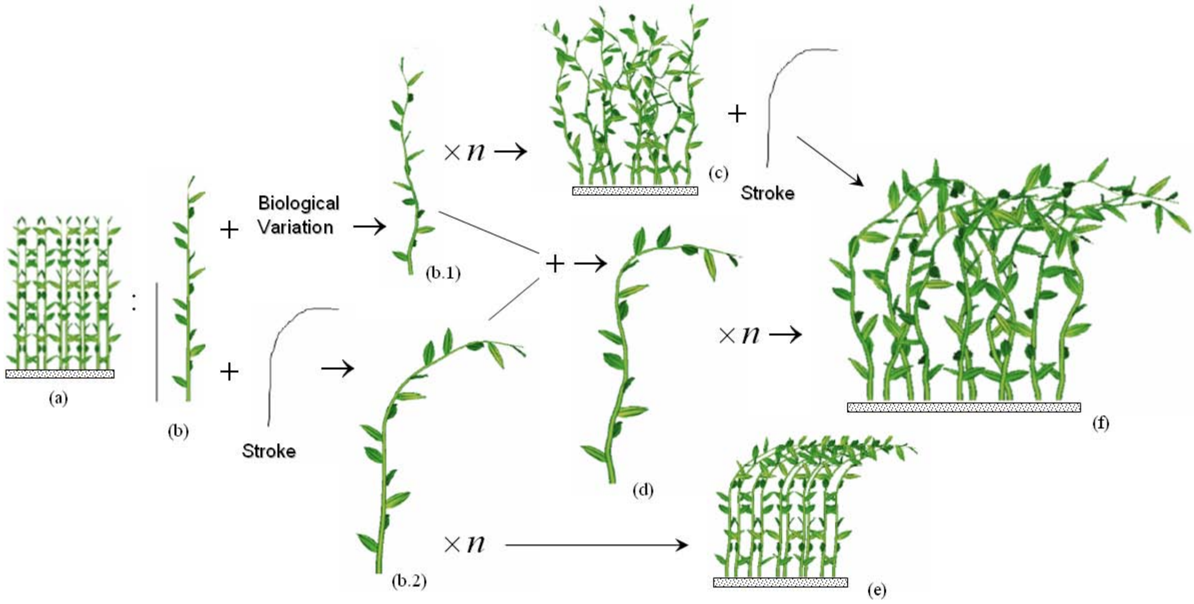


**Figure 10:** *A pipeline from original plant model on the far left to a collection of plants on the far right created by combining stroke and biological growth variation in each instance.*

growth. More precise control of motion indicators was requested: one participant asked to be able to map specific motion indicators to influence only specific parts of the plant. Although participants commented very positively about the smart selection technique, two suggested adding an intermediate selection visualization feedback indicating undetermined branches through color. Finally, one participant suggested we support selecting long paths by specifying only start and end branches of a selection and automatically selecting intermediate branches. We are planning to address and implement these suggestions in the future.

## 6. Conclusions and Future Work

We described a method for directly controlling branch stem and shape in plants for the purposes of creating variation among instances of the same plant model. The proposed method uses the 3D Tractus, a physical 3D interface, to allow the user to interact with the plant model intuitively in 3D and communicate shape information by drawing the intended shape in a 3D environment. To facilitate ease of specifying shape for numerous branches a method for propagating stroke shape through multi-resolution editing was used and a smart selection algorithm was used to associate strokes with branches. Further indicators of shape such as direction of light, wind or other environmental factors could be added by drawing sets of lines which indicate the direction and strength of these factors directly to the 3D environment.

The associated branch shape strokes were then used as input to a growth simulation framework. The simulation results in variation (aside from stroke variation) by adding variation through growth. Overall, the simulation models the randomness in growth while trying to maintain the intended curvature of the branches and stems as indicated by the user-defined strokes. In this manner, the overall shape of stems and branches is as intended, with subtle variations in the shape introduced through free-handedness of sketch and simulation. The preliminary user evaluation we performed demonstrates the potential effectiveness of our approach in creating varied plant models.

Extending this framework of control and 3D creation beyond stems and branches to plant organs could be a useful direction of future work. This may include not only creating and controlling the shape of plant organs, but also their spatial 3D distribution and orientation on the plant.

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