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Multi-Granular Trend Detection for Time-Series Analysis

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Fig. 1. Left: automated trend detection in combination with manual interaction finds two opposing key trends in the data (CO2 intensity of economic output: kg CO2 per 2005 PPP $ of GDP [13]). Middle: selecting only the subset that is part of the peak at T1, directly shows that this subset is not part of the peak at T2 (homogenized daily amount of precipitation for 240 weather stations [21]). Right: different visual styles help (de-)emphasize different properties of the detected trends.

Abstract— Time series (such as stock prices) and ensembles (such as model runs for weather forecasts) are two important types of one-dimensional time-varying data. Such data is readily available in large quantities but visual analysis of the raw data quickly becomes infeasible, even for moderately sized data sets. Trend detection is an effective way to simplify time-varying data and to summarize salient information for visual display and interactive analysis. We propose a geometric model for trend-detection in one-dimensional time-varying data, inspired by topological grouping structures for moving objects in two- or higher-dimensional space. Our model gives provable guarantees on the trends detected and uses three natural parameters: granularity, support-size, and duration. These parameters can be changed on-demand. Our system also supports a variety of selection brushes and a time-sweep to facilitate refined searches and interactive visualization of (sub-)trends. We explore different visual styles and interactions through which trends, their persistence, and evolution can be explored.

Index Terms—Interactive Exploration, Trend Detection, Time Series.

1 Introduction

Due to our increased ability to monitor processes and record detailed information, a large body of data is readily available that describes the behavior of complex processes over time. Sensors in our mobile phones and cars, or more conventional sources such as weather stations, supply continuous information on the state of different variables over time. In this paper we focus on one-dimensional time-varying data, that is, time-series data. An important type of time-series data are so-called ensembles: the set of simulation results of intricate models for varying starting conditions and parameter settings. Ensembles give an indication of the possible spread of a model over time and contain exact traces of the different inputs, making them highly valuable for domain experts [26]. They are commonly used in weather prediction [8, 16], climate change [20, 38] and hurricane prediction [12, 35].

The visual analysis of time-series data quickly becomes infeasible if the raw data is used directly. The high complexity of the data sets, combined with their inherent uncertainty, makes it difficult to analyze. Hence there is a growing body of visualization literature [3, 26] that attempts to visualize uncertainty in data.

One common approach to visualize uncertainty, while also decreasing complexity, is to reduce the data to its main statistics. Heat-maps and fan-charts, for example, give a statistical overview of the distribution of the data. The abstraction of these maps is their main strength, but also their main weakness. The strong reduction of the data creates structure but at the same time runs the risk of overemphasizing the extremes and “hot spots”. Without knowledge of the individual entities that comprise the data such representations may be misleading. Other options to display uncertainty include the display of regular distribution plots [31], and uncertainty isolines [30].

An alternative approach to displaying uncertain data is to enforce more structure on the data. Agglomeration via trend detection reduces complexity while maintaining a significant part of the information contained in the original input data. Trend-detection groups entities that behave similarly over an extended period of time into trends. The extent to which time series “behave similarly” and the notion of an “extended period of time” are not predetermined. However, results and interpretation are dependent upon these analytical parameters. We think of a trend as a set of entities such that all entities in the trend are a small distance away from their neighbors. See Fig. 2 for an illustration. This criteria of closeness results in trends that reasonably match with expectations. There may be more aspects that affect human perception of trends, though, such as the distribution of elements.

A more abstracted view of the data reduces the cognitive load for the user and may help detect structure that is hidden when all information is shown. In this sense trend-detection serves a similar goal as edge-bundling [18, 19, 28]. Trend detection, and the subsequent visualization of the detected trends, also performs well for multi-modal time series or ensembles.

Trend detection is not without challenges. The visualization of
Contributions. We propose a geometric model for trend-detection in one-dimensional time-varying data, inspired by topological grouping structures for moving objects in two- or higher-dimensional space. Specifically, our model builds on the work by Buchin et al. [5] and Van Kreveld et al. [40]. Trends are detected using three natural parameters: granularity, support-size, and duration. The model is firmly rooted in geometrical methods for trend detection and trends have a clean mathematical definition. This mathematical soundness allows for provable guarantees on the detection of trends.

We define a series of tasks and visualization criteria for trend detection systems. Based on these tasks we then explore different visual styles and show how they may affect the task-appropriateness of the system. Distinct styles affect the displayed information differently and we discuss their trade-offs and complications.

Finally, we discuss several tools that help to interactively explore the data via a computer-assisted model. Different selection brushes, fixed starting conditions, and a time-sweep allow the user to decompose and construct trends on-demand.

Related Work. The visualization of uncertainty is an important current area of visualization research [26]. In uncertainty visualization [3, 32] a general stochastic uncertainty in the data is assumed. This uncertainty may be based on inexactness of the measurements or of the model. To represent this uncertainty the probability density function (PDF) is visualized. Overview statistics (such as the mean and standard deviation) are used to display the variability in the PDF over time or position. Different glyphs have been proposed to visualize this variability, for example, box plots, violin plots [17], and summary plots [31]. Higher-dimensional data may be visualized using (probabilistic) isolines to display uncertainty [2, 29, 30, 41]. Local surface distortion [15] and animation [4] have also been applied to display uncertainty in higher-dimensional data.

Ensemble visualization differs from uncertainty visualization, as the different data series are not stochastic samples, but correspond to exact instances of the input. The ability to analyze and correlate data series, and thus different inputs, make ensembles very valuable for domain experts [26]. Previous work on ensemble visualization has mainly focussed on representing two-dimensional and three-dimensional ensemble data. Sanyal et al. [37] proposed a spaghetti-like representation of the ensemble, highlighting different features in the data set. Mirzargar, Whittaker, and Kirby [24] recently proposed a curved box plot to display ensemble information. They use the model of data depth to determine a multi-dimensional distribution function. However, similar to PDF-based visualizations they are able to handle only uni-modal density functions. Ferstl, Burger, and Westermann [11] use trend detection to agglomerate the different ensemble members. They use principle component analysis (PCA) to detect trends in the ensemble. PCA, however, is not intuitive and changing the dimension for PCA may not give clear changes in trend detection. Dykes and Brunsdon [10] use ensembles to investigate the distribution of a single data variable across space and scale. Potter et al. [33] argue that presenting all information in a single display is not required. They propose a multiple linked displays framework to study ensembles. Finally, multi-dimensional ensembles may also be projected down to one-dimensional functions. Demir, Dick, and Westermann [9] combine histograms with local one-dimensional ensembles and brushing techniques to interactively explore a three-dimensional ensemble.

Time-series data, similar to ensembles, consist of a set of time-varying series. In contrast to ensembles though, the series need not stem from a single model, but may be uncorrelated. Time series are often used as a part of larger visualization frameworks, for example, in small multiples. The comparison of different time series and trend detection within groups of them has received some attention. Stacked graphs [6] can be useful to visualize several functions at the same time, but comparisons between different series may be difficult. Recently Horizon Graphs [27, 34] have been introduced as a tool to display multiple time series while allowing easy and quick comparisons. Other work on trend detection is based on the topological grouping structure, introduced by Buchin et al. [5]. Intuitively, a group is a sufficiently large set of entities (for example, animals, people, or cars) that move together during a sufficiently long time interval. Buchin et al. present an efficient algorithm that, given the trajectory data, can compute all maximal groups, and the relations between these groups (that is, groups $G_1$ and $G_2$ merge into group $G$ at time $s$, and $G$ splits into groups $H_1$ and $H_2$ at time $t$). Recently, van Goethem et al. [39] extended their work to efficiently change the group parameters, that is, the required minimum group size, the minimum group duration, and the maximum distance between the group members. Their work allows a user to interact with the data set to explore the effect of the different parameters. Kostitsyna et al. [22] and Löffler et al. [23] extend the work of Buchin et al. to environments with obstacles. Van Kreveld et al. [40] recently observed that in dense environments the original definition by Buchin et al. may not capture the nature of a group well. They propose a slight variation on the definition for this setting. This adapted definition, however, does lead to a higher computational cost.

Organization. We formally define the problem we study in Section 2. There we discuss the concepts involved in trend detection and identify primary tasks. Section 3 presents the algorithmic foundations of our work. We first describe the work by Buchin et al. and then explain a simpler and faster algorithm for trend detection. Section 4 discusses a variety of visual encodings that may be used to represent trends and explains how these visual encodings relate to the primitive tasks. In Section 5 we explain our tools for interactive exploration. Using the results of all previous sections, in Section 6 we show how to detect correlations in two real-world examples with our system. Section 7 discusses the limitations of our approach and Section 8 concludes with a general discussion and possible directions for future work.

2 Problem Definition

In this section we first define the concepts of time series, ensembles, and trends. We then analyse the problem of trend detection and define the tasks that should be supported by any trend-detection system. We also define several aesthetic criteria that should be taken into account to efficiently visual the detected trends.

2.1 Preliminaries

Time series. A time series is a time-ordered sequence of data points that describes how a variable changes over time. Each data point $d$ can be described by a pair $d = (t, v)$, where $t$ is the time-stamp at which the data has value $v$. We consider only time series that have exactly one data-variable, hence $v$ is assumed to be a single real number. The length of a time series is the number of data points. We assume that the data changes linearly in between consecutive data points. Thus, we can interpret a time series as a piece-wise linear function describing the
change in a variable over time. We do not require that the data points are uniformly spaced in time.

A collection of time series is called time-series data and consists of \( n \) different time series. Each of these time series has at most \( \tau \) data points. For ease of description we assume that all time series have exactly the same time span \([t_s, t_e]\).

**Ensemble.** An ensemble is a specific form of time-series data where all time series originate from (a perturbed version of) the same model. All time series describe the change of the same variable over time but have slightly perturbed starting conditions or models. Consequently, these time series are strongly correlated at the initial time-stamp and as time increases become more diverse. Very well known examples include weather predictions and runs of climate change models.

**Trends.** In trend-detection we are interested in detecting the hidden structure in an input data set. That is, we want to detect whether there are several time series that behave similarly over an extended period of time. We say that such a set of similar time series form a trend, and that the time series comprising it form the trend-members. When time series “behave similarly” and what an “extended period of time” is, depends on the model used. We use the grouping structure as the base for trend detection. Intuitively this means that all entities comprising a trend should be at most a small distance \( \epsilon \) away from their neighbors in the trend. A more formal definition is given below. See Fig. 2(b).

Important properties of a trend are its support, duration, range, and its distribution. The support of a trend is the number of time series that are part of the trend, the duration is the length of the time interval during which the time series behave similarly. The range of a trend is the interval between the highest valued and lowest valued time series in the trend, and the distribution of a trend indicates where exactly the time series making up the trend lie within the range of the trend. For a given trend \( T \), a subset of the time series in \( T \) may form a trend \( T' \) that has a longer duration (but a lower support) than \( T \). We refer to such a trend as a sub-trend of \( T \). See Fig. 2(c) for an illustration.

We focus on finding and displaying only those trends that are present initially, that is, at time \( t_s \). There are several advantages to focussing only on initial trends. First, the detection of trends starting at a fixed point in time naturally captures the uncertainty in the ensembles that we consider (for example, weather predictions). As a result, the trends are naturally diverging. Note that by changing the starting position users can still browse all parts of all different trends. Second, the grouping algorithm runs significantly faster than in the general case, allowing for better user interaction.

By considering only trends that start at \( t_s \), the trends form a forest [7]. We may have several trends with large support and a short duration that form the roots of the trees in our forest. Each of these trends may have several children that represent sub-trends of slightly lower support and larger duration. In turn, these trends may have sub-trends of their own, thus resulting in a tree structure.

### 2.2 Problem Analysis

An input instance consists of a set of \( n \) time series. Each time series is a piece-wise linear function defined over the time-interval \([t_s, t_e]\). The objective is to detect patterns, at arbitrary granularities, to find correlations between different input time series. We assume a computer-assisted model in which the user interacts with automated trend detection to analyze the data. Within the model, we specify a series of primitive tasks that should be supported by the system to enable exploration and correlation of the data. We also specify different visual encodings that affect the usability of the system.

Aigner et al. [1] describe a set of tasks that are involved in the analysis of time-oriented data. These tasks include classification, clustering, search and retrieval, pattern discovery, and prediction. Our approach is focussed on the clustering task and as such all primitive tasks described below are focussed around the effectiveness of the clustering.

In a clustering task the data is grouped based on similarity, in our case inter-entity distance. Clustering abstracts the data and therefore it is important that it does not falsely represent the underlying data. Manual pattern discovery (automatic detection of interesting patterns), and prediction (infer the evolution of data in the future) may be supported through the use of our clustering approach, however we do not support the automated computational support of these tasks.

**Primitive Tasks.** To detect coherence in the data several primitive tasks need to be performed. These tasks are centered on two core concepts: estimating trend statistics and determining connectivity within the detected trends. The tasks support a more abstract level of data processing where similarly behaving items are clustered in trends.

- **T1a** Estimate support of a trend.
- **T1b** Estimate range of a trend.
- **T1c** Estimate distribution inside a trend.
- **T2a** Determine behavior of (a subset of) time series over time.
- **T2b** Determine how granularity affects the trend formation.
- **T2c** Determine connectivity of the trend structure.
- **T2d** Correlate different trends.

The combination of different primitive tasks allows more complex questions to be answered. What is the strongest supported trend in the data and how large is the range? (T1a, T1b). How does the range of a group of time series change over time? (T1b, T2c) . Are there time series that are included in two or more specific trends? (T2a, T2b, T2d). Do the time series included in a given trend behave consistently, or do they form finer trends at other granularities? (T2a, T2b). How do the initial conditions affect future behavior? (T2c, T2d).

An effective visualization should support the majority (if not all) of the primitive tasks. Not all tasks are enabled equally by different visualizations though. We focus more on the effects of visual encoding on the primitive tasks in Section 4.

**Visual Encoding.** Besides the support of primitive tasks, an effective visualization should also aim to reduce the effort involved. Clear visual cues help reduce the cognitive load by pre-structuring the presented information. Reducing the cognitive load improves task-efficiency and maintains clarity for complex data sets. We distinguish several aspects that may positively affect the task-effectiveness.

- **V1** Firm grounding in input data.
- **V2** Clear trend separation.
- **V3** Low visual complexity of trends.
- **V4** Continuity of shapes in trend-structure.
- **V5** Visual distinction between uni-modality and multi-modality.

To properly judge relationships within the data, the visualization should display only information that is firmly grounded in the input data (V1). This (nearly) trivial observation can be difficult to ensure in practice and has often been overlooked. The display of range (T1b), affects the perceived distribution (T1c) of a trend, unless explicitly visualized. Support (T1a) and range (T1b) together define the local density at each point in time, but either may overshadow the other, affecting the perceived density. Furthermore, a visualization should not introduce salient features that are not present in the input data. This is problematic for automated trend detection since the (arguably artificial) begin- and end-point of a trend are highly visible.

As trends may overlap, clear trend separation (V2) ensures that different trends can easily be kept apart. This allows different trends to be related and emphasizes the structure between trends (T2a, T2c, T2d). Reducing the visual complexity of the represented trends (V3) helps reinforce this structure even further and shifts focus from exact representations to a higher-level structure. We note that this is in stark contrast with the first criterion (V1) as simplifying the data reduces the strength of the relation to the original input data. The low visual complexity of trends is improved further by the (smooth) continuation of trends (V4). We ensure that trends split into sub-trends continuously and so further emphasize the structure in the trends (T2c, T2d).

When the distribution inside a trend is not explicitly encoded, visualizations may incorrectly imply distributions with are not in fact
present in the data. For example, by solely encoding the range of a trend, a uniform or uni-modal distribution may be implied. In many cases this is, however, not a fair implication. By making a visual distinction between uni-modal or multi-modal distributions (VS) we can help parse the underlying structure of trends (T2a, T2b).

3 Computing Trends

In this section we describe how the work on trajectory grouping by Buchin et al. [5] and Van Kreveld et al. [40] can be used to detect trends. We first revisit their definitions, and see how they relate to trends in time-series data in Section 3.1. The algorithms for computing trajectory grouping structures may be used to detect maximal groups (and as a result, trends) that begin and end at any arbitrary position in time. However, in our setting, we are interested only in maximal groups that start at the initial time \( t_s \). In Section 3.2 we present a simple algorithm, based on the one by van Kreveld et al., to compute all maximal groups that start at \( t_s \).

3.1 Trajectory Grouping Structure

Buchin et al. [5] consider the problem of detecting maximal groups in trajectory data. They define a \((m,e,\delta)\)-group to be a set of at least \( m \) entities (e.g. animals, people, or objects) that travel together, with respect to distance parameter \( e \), during a time interval of length at least \( \delta \). A set of entities \( G \) is together if and only if it is \( \varepsilon \)-connected: that is, if for every pair of entities \( a,b \in G \), there is a chain of entities \( a = c_1, \ldots, c_k = b \) such that for any pair of consecutive entities \( c_i \) and \( c_{i+1} \) the distance is at most \( e \). See Fig. 3 and Fig. 5(a).

Consider each time series as the trajectory of an entity that moves in \( \mathbb{R}^1 \). We then observe that an \((m,e,\delta)\)-group \( G \) corresponds to a set of (at least \( m \)) time series that behave similarly, that is, they are \( \varepsilon \)-connected at any time, during a time interval of length \( \delta \). Indeed, the notion of a group naturally corresponds to a trend.

Let \( G \) be an \((m,e,\delta)\)-group on time interval \( I \) of size \( |G| > m \). All \( \binom{|G|}{m} \) subsets of size \( m \) also form \((m,e,\delta)\)-groups on interval \( I \). We are interested only in maximal groups \( G \): groups that are maximal in size and duration (that is, we cannot add any entities to \( G \), nor can we grow the interval on which \( G \) is \( \varepsilon \)-connected). In the remainder of this paper, we refer to maximal groups simply as groups. Buchin et al. [5] show that, in a collection of \( n \) trajectories of length \( \tau \), there are at most \( O(\tau n^3) \) maximal groups, and they can be computed in \( O(\tau n^3) \) time.

In the definition of groups as given above, the entities in a (maximal) group \( G \) may be \( \varepsilon \)-connected through entities that are not in \( G \). If the set of entities is very dense this may yield somewhat unintuitive results, see Fig. 4. Therefore, van Kreveld et al. [40] give a refined definition of group in which the entities in group \( G \) have to be \( \varepsilon \)-connected using only entities that are also in \( G \). The number of maximal groups according to this definition is still \( O(\tau n^3) \). Computing all of them takes \( O(\tau^2 n^4) \) time. Since our ensembles are likely to be dense, we consider this refined version of groups.

**Algorithm 1 ComputeMaximalGroups(\( T \))**

**Input:** a non-empty set \( T \) of time series in the interval \([t_s, t_e]\).

**Output:** the set \( G \) of maximal groups starting at \( t_s \).

\[ \{ \text{Find initial maximal } \varepsilon \text{-connected sets:}\} \]
1: Sort \( T \) by increasing their value at \( t_s \).
2: Scan through \( T \) to find all maximal \( \varepsilon \)-connected sets at time \( t_s \).
3: for all initial maximal \( \varepsilon \)-connected sets \( G \) do
4: Let \( E \) be the ensemble induced by all the time series in \( G \).
5: Sweep \( E \) to find the first \( \varepsilon \)-split at time \( t' \), at which \( G \) splits into \( G_1 \) and \( G_2 \). Let \( t_r = t_s + \varepsilon \) and add \( G \) to \( G_r \).
6: if \( t' \neq t_r \) then
7: Add \( G \) as a group starting at \( t_r \).
8: \( G_1 = \text{ComputeMaximalGroups}(G_1) \)
9: \( G_2 = \text{ComputeMaximalGroups}(G_2) \)
10: Add sub-groups from \( G_1 \) and \( G_2 \) lasting longer than \( t' \) to \( G \)
11: return \( G \)
inverted, changing which pairs of time series are consecutive. This
again affects the future intersect- and split-events of the time series in-
volved. We remove the old intersect- and split-events from the priority
queue, and add the new events to the queue.

At a split event the current maximal group $G$ stops forming an $\varepsilon$-
connected group. We report $G$, and split the group in two $\varepsilon$-con-
ected groups $G_1$ and $G_2$. As subgroups may stop earlier than the group they
split from, we restart the computation at $t_0$ for both subgroups.

**Analysis.** Each of the $n$ time series has at most $\tau$ data points. It follows
that there are at most $O(\tau n)$ vertex events, and $O(\tau^2 n^2)$ intersec-
tion events. At each split-event at least one new maximal group is found.
There are at most $n$ maximal groups that end at $t_e$, each containing
a single element. As the groups can only split into sub-groups, the
number of split events is at most $n - 1$. Handling a vertex event or
an intersection event takes $O(\log n)$ time. Thus, in between the split-
events we spend at most $O(\tau^2 \log n)$ time. Since there are at most
$O(n)$ split events the total running time is $O(\tau n^3 \log n)$.

If we consider yet another variation on the definition of group, in
which we require a (sub)group $G$ to be $\varepsilon$-connected only from the time
it comes into existence (that is, because a larger group split into
$\varepsilon$-connected only from the time $t$ they split from). We restart
the computation at $t_0$ for both subgroups.

The encoding of trend structure and support using a centerline is
a plausible approach. We do, however, note several issues that might
occur under boundary conditions. Strongly supported trends that are
highly correlated and have a small range may be overshadowed by the
centerline ($\neg$V1). This can partially be resolved by globally scaling the
width of the centerlines. In the exact opposite case, where the center-
line is minimal compared to the range of the group, the centerline need
not be the most visually salient feature. This might lead to an overes-
timation of the support of a group as the range is visually dominant.
Finally, using the mean position for the centerline implicitly encodes a
uni-model distribution ($\neg$V5). This is not always justified, specifically
when trends split. We discuss possible solutions in Section 4.2.

Besides encoding support on the centerline, we may also encode it
through the use of transparency (see Fig. 6(a)). Here the transparency
of a trend is directly correlated with the support of a trend. To ensure a
consistent smooth change we linearly interpolate the gradient in each
trend to match at trend splits. The main disadvantage of transparency
is that future trends may become less discernable, especially when
many trends overlap ($\neg$T2a, $\neg$T2c). Furthermore, the strength of a
trend is not solely defined by the support, but also by the range. A
trend with similar support, but smaller range is more firmly present in
the data. However, a trend with a smaller range (and similar support)
will be less visible in the visualization ($\neg$V1).

**Distribution.** The distribution within a trend supports analysis of
trends at other granularities than the current (T1c, T2a, T2b). The
extremes, quartiles, and mean are an indication of trends at different
granularities. Re-introducing the statistical information for each trend
increases information density, however, that is at odds with our goal
to simplify the trend structure (V3, V4). We mainly focus on display-
ing the range of possibilities using the extremes of the trend. A
similar approach might be applied using the quartiles as boundaries.
We purposefully do not include both as this visually reinforces a uni-
modal distribution, whereas a significant part of our data is likely not
uni-modal. We investigate several options to visualize the range and
compare their weaknesses and strengths.

The most basic visual style simply displays the complete range (see
Fig. 6(b)). That is, we display the area in between the maximum and
minimum extreme. We simplify the outliers to remove any (meaning-
less) noise (V3). Displaying the extremes does not give any informa-
tion on the distribution of time series within the group. All elements
are at least $\varepsilon$-connected, but the distribution is not guaranteed to be
uniform or uni-modal. There may be large sections that are enclosed
in between the extremes, but that are not supported by any time series
in the trends. This is particularly the case when trends split into several
sub-trends. This “illusion of presence” is also a problem for fan charts
when the distribution of the data is multi-modal ($\neg$V5).

We present two possible approaches to counteract this illusion.
First, we may increase the information encoded in a trend. For exam-
ple, we might encode the (complete) distribution by using a heatmap
(see Fig. 7(a)). Introducing more information reduces the illusion
of presence by increasing the accuracy of the representation (V3, V5).
Of course there is a trade-off between simplification and information.
4.2 High-level Structure

Our geometrical model clearly defines when a group (or trend) comes into existence and when it ceases to exist. However, the resulting trend structure, but within a trend all information is abstracted. The result is a harmonious display of the data as the group and centerline are in complete agreement (see Fig. 7(b)) (V3).

There are some visual artifacts associated with this style. First, a consistent range may be achieved by offsetting the centerline along the vertical axis. Curvature, however, will result in an appearance of non-uniform width. Hence the range might be interpreted as accurate by the user after all. A perpendicular offset of the centerline prevents this, but causes the range to be non-uniform along the trend. Consequently, it is hard to compare the range of different groups (¬V1). Second, trends and sub-trends become non-continuous. A discontinuity occurs at the common boundary as the mean range of trends and sub-trends do not match up (¬T2c, ¬V4). This visual discontinuity may be harmful in situations with many overlapping groups. Furthermore, it is a strong visual cue that has no firm grounding in the input data (¬V1).

To prevent discontinuities at the boundaries we simplify the boundary instead. We sample the range along the trend at regularly fixed intervals. These sample include at least the start and end of each trend. Using a low resolution sampling (up to three per group) we simplify the input but remove any visual discontinuity (see Fig. 8(a)).

Splits. Trend splits have high visual impact: just before a trend splits there must be an area of height $\varepsilon$ that does not contain any time series and after the split this area does not exist anymore. If we display trends uniformly in their full range, there will hence be a strong visual break at a split (¬S1). The data, clearly, is neither uniform nor uni-modal around a split (after all, there is an $\varepsilon$-split between at least two of the items). We reduce the saliency of $\varepsilon$-splits by visualizing the area devoid of time-series occuring before an $\varepsilon$-split.

Let $T$ be the trend that splits into two sub-trends. Let $\Delta$ be the time series that are part of the newly formed upper trend and $\Delta'$ the time series that are part of the lower trend. We compute the lower envelope of $\Delta$ and the upper envelope of $\Delta'$ (see Fig. 9(a)). Let $i$ be the last intersection of these two envelopes that falls inside $T$. The two envelopes from $i$ onwards define an area $A$ inside $T$ that is devoid of any supporting time series (see Fig. 9(b)). We draw $A$ with reduced opacity, thus reducing the saliency of the trend split itself (see Fig. 8(b)).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{(a) The upper-envelope is the pointwise maximum of a set of poly-lines (red). (b) The lower envelope of $\Delta$ and the upper envelope of $\Delta'$ define the area $A$ devoid of items.}
\end{figure}

Centerline. While the centerlines reinforce the structure of the trends, the vertical connections between centerlines emphasize the visual discontinuities in the detected trends at splits (¬V1). We explore different visual styles to reduce the disruptive influence of these connectors.

The connectors between centerlines of trends are not part of the original input data. Hence, we aim to reduce their saliency. One option is to color the connectors differently to emphasize that they are not part of the data (see Fig. 10(a)) (V1). The different color connectors, however, make the visualization more complex and do not form a logical connection with the centerlines. Alternatively, dotting or dashing may help to de-emphasize the connectors (see Fig. 10(b)).

We may decide to not draw connectors at all. As discussed before, placing the centerlines along the mean implicitly encodes a uni-modal distribution. This is not always justified, specifically at splits. Hence, we can decide to reposition the centerline to prevent a visually salient split. Let $T$ be the main trend and $\Delta$ the sub-trend that has the largest support among all sub-trends. We compute the mean centerline of $T$ as well as the mean centerline of the subset of time series in $T$ that are also part of $\Delta$. The resulting centerline for $T$ is the linear interpolation of both centerlines. Let $x_c, x_s$ be the $x$-coordinate of the start, respectively end, of $T$. The final centerline $C(x)$ is positioned at $(x_c - x) / (x_c - x_s) \cdot T(x) + (x - x_c) / (x_c - x_s) \cdot S(x)$. For other sub-trends a similar connecting centerline is computed, that is cut off as soon as it intersects $C$. Connections to sub-trends may be displayed either dotted or regular (see Fig. 10(c)). Repositioning the centerline reinforces the trend structure, but reduces the grounding in the input data (¬V1, V4).

5 Exploring Trends

Our method supports three parameters to steer the automated trend detection: granularity, duration, and support (see Fig. 11). Varying the granularity, controlled by the $\varepsilon$-parameter, allows detection of coarser or finer trends. Filtering on duration prevents the detection of too short trends, and filtering on the support prevents trends with low support.

Trend Granularity. The detection of trends is based on a singular parameter that determines a threshold on the maximum allowed distance between consecutive elements. By changing the $\varepsilon$-parameter, the different granularities of trends may be investigated (T2a, T2b, T2c). A smaller value of $\varepsilon$ results in strongly coherent trends and allows only minor deviations from the trend. While this may capture the most...
strongly formed trends, small deviations may cause other trends to not be detected. Larger $\epsilon$ values allow more variation in the trends, ensuring that higher-level processes are captured in the trend detection.

**Support Size and Duration.** Besides the $\epsilon$-parameter we allow the user to also filter on the size and duration of trends (T1a). The support parameter filters out trends that are not supported by a sufficient number of time series. As the trends form a forest, filtering on support removes small trends, starting at the leaves of the trees. By contrast, the duration parameter filters trends based on a minimum duration, starting from the roots of the trees in the forest. The combination of both is a powerful tool that allows the user to focus on specific trends.

### 5.1 Trend Interaction

Automated trend detection finds trends of arbitrary granularity in the data. However, users may be interested in the behavior of only a part of the data based on the information gathered (T2a). Manual interaction ensures data can be explored in an iterative manner while being supported by automated detection. Our approach supports three types of trend interaction (selection brushes, fixed initial configuration, and a time-sweep) as well as highlighting and selection.

**Selection Brush.** We support three types of brushes that allow selection of a subset of the original input time series (see Fig. 12(a)). The all brush selects only the data that passes through all brushed areas. This can be used to select data that follows a specific pattern (T2a, T2b). The any brush selects time series that pass through at least one of the brushed areas. It may be used to refine selection while allowing the user to select several diverging patterns. Finally, the deselect brush deselects all time series that pass through at least one of the brushed areas. It complements the any brush, allowing the same selective capabilities.

**Initial Configuration.** Users may want to study the behavior of different initial parameters settings (T2a, T2d). But if the subsets each diverge over time, this requires a coarse level of trend detection that may group all subsets together at the start. By selecting the initial configuration, users can define which subsets should remain separated (see Fig. 12(b)). Similar to the brushes, users can draw intervals at the initial time-stamp. Time series can only form groups within the same interval, so different starting conditions can be kept separate even when analyzing the data at a very coarse level. The initial configuration tool is more powerful in this sense than the basic selection brushes.

**Time Sweep.** Our approach detects only trends that start at $t_s$. By changing the initial starting position we can also detect trends starting at different points in time. We visually encode the starting position by a vertical line at the start of the time series. The user can select and drag this line to initiate the algorithm from a later point in time (see Fig. 14). The time-sweep in combination with selection brushes allows exploration of correlations at later positions in time (T2a, T2c). The time-sweep allows us to find all the groups included in the complete grouping structure defined in Section 3.1. Nevertheless, for any particular setting only a subset of the groups are detected.

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Fig. 10. (a) Encoding the connectors as artificial by using a different color. (b) Using dashing to encode the connectors. (c) Removing the need for connectors by interpolating the different centerlines.

Fig. 11. The automated detection of trends can be steered via three natural parameters. Duration filters groups from the root of the tree, whereas support filters groups from the leaves.

Fig. 12. (a) Selection brushes (all brush in dark blue and any brush in light blue) can be used to select the time series. Trend detection then operates only on the subset (3h forecast humidity at 2m in percent (BHM) [25]) (b) Selecting an initial configuration allows for trend detection in models with similar starting conditions. (3h forecast dew point temperature at 2m in degrees Fahrenheit (BHM) [25])

Fig. 13. Forward- and backward-highlighting of trends allows temporal exploration of structures. (a) Forward highlighting emphasizes trend development. (b) Backward highlighting emphasizes the trend origin.
Highlighting and Selection. Highlighting shows the structure of the currently selected trend (T2a, T2c, V4). Forward highlighting (see Fig. 13(a)) highlights all future possibilities branching out from the currently selected trend. Backward highlighting (see Fig. 13(b)) highlights the path of origin of the currently selected trend. It may be used to analyse coherence in the past tracks. Highlighting uses a colored casing for the selection - a distinctive light blue in Fig. 13. Alternatively, the highlighted selection may be displayed in a different color.

Selection allows trends to be layered in different orders. Complete subtrees can be moved to the front or the back of the view. The user can also select subtrees and place them partially transparent in the background to reduce visual clutter (see Fig. 15).

6 Example Applications

We now show how our system can be used to analyze real-world data sets. We first discuss a general time-series data set that concerns the value added by industry to the GDP (GapMinder; data provided by the World Bank [13]). Secondly, we explore an ensemble from the NOAA SPC Plume Viewer [25]. The ensemble is built around two core models with six positive and six negative perturbations per model.

We illustrate how the different exploratory tools allow the detection of trends in the data and help correlate different time series.

Time-series data. The GapMinder data contains approximately 200 time series representing the value (in percentage) added by industry to the GDP of different countries across the world. Given the number of time series in the data set, direct visual analysis is infeasible. Animation can help reduce the amount of information displayed at any point in time, but might not be effective [36]. We display all information and combine automated trend detection with manual interaction to find key trends. As the data set is very dense we start our exploration with a very small setting of $\varepsilon$. The resulting trend structure appears to imply that there might be two major trends that start at the top and bottom of the data set (see Fig. 16(a)). We split the data set by fixing the initial intervals within which we detect trends. We can now safely increase $\varepsilon$ and note that there appear to be two main trends that cross (see Fig. 16(b)). There is no clear outcome, though, as both trends now cover the complete area, so there might be a large bias in our observation. After changing the trend detection and checking different subsets, we notice that this trend is most strongly supported in the extremes of the initial distribution. We further restrict our input and note that, indeed, there is a strongly supported trend where the value added by industry significantly reduces (see Fig. 16(c)). Comparatively there is only a small trend where the value added by industry is on the rise.

Ensembles. The diverging nature of ensembles makes them a natural match with the trend structure we compute. The ensemble data we consider here are a forecast for the dew point – the temperature at which atmospheric water vapor condenses. There are two core models (the WRF-ARW and NMM-B NAM Model), and for each model 12 different perturbations. An initial exploration of the data indicates that there is a strong trend that splits off a minor sub-trend near the end (see Fig. 17(a)). We select different trends and subsets using the selection brushes. By refining the detected trends, we find that there are two very fine trends with reasonable support that significantly depend on the initial parameterization (see Fig. 17(b-c)). When we correlate the
time series back to the input data we note that the bottom trend consists solely of time series resulting from the WRF-ARW model (and mainly the negative perturbations). The top trend, by contrast, consists solely of time series resulting from the NMM-B NAM Model.

7 LIMITATIONS

While the computer-assisted analysis of trends using our visualization appears effective, there are some limitations. When many subtrends overlap, the visualization is problematic due to the occlusion of many subtrends (see Fig. 18(a)). While trends can manually be sorted on the \( z \)-axis, this does not help in getting an overview. It would be desirable to clearly visualize all subtrends even when they overlap. A solution could be to merge the different subtrends into larger groups, but interconnectivity between different subtrends should be maintained. This is problematic as subtrends might be interleaved. Animation, interaction and other modes of visual comparison [14] may be useful.

The detection of trends at different granularities helps to get an overview of the data and its structure. However, it may be desirable to detect trends at different granularities at the same time (see Fig. 18(b-c)). When a small group of entities is clearly separated from the rest of the ensemble, it is plausible to group them as a trend even when they are relatively far apart from each other. Currently the granularity of the detected trends is fixed across the complete ensemble. Therefore we cannot distinguish fine-trends and detect a coarser-level trend at the same time. This behavior is consistent with our model.

8 DISCUSSION AND FUTURE WORK

We proposed a geometric model that guarantees detection of trends (according to a precise mathematical definition) when they are present. Our model is based on three parameters: granularity, support-size, and duration. We explored different visual styles and showed how they relate to the primitive tasks that a trend-detection system should support. Finally, we introduced several tools for interactive exploration.

Combining automated trend-detection with interaction helps to quickly get an overview of the data and zoom in on trends in subsets of the data. Because trends are guaranteed to be detected, visual analysis is supplemented with automated detection and trends are less likely to be missed. While our approach looks promising, it is not validated by external users. Hence, in future work, it would be important to perform user studies to validate our approach.

We detect only those trends that start at time \( t_s \). Naturally it would be interesting to also explore the complete trend structure, where trends may split into subtrends and then merge again into larger trends. The visualization of this braided graph of trends is a challenging problem, and might require the display of subtrends inside other trends as well as their connectivity.

Our visualization is not as simple as it could be. Trends sometimes have a jagged appearance and additional simplification and smoothing could be applied. However, such simplification necessarily removes the visualization further from the input data. After all, some sharp features might in fact be critical features of the data.

Furthermore, if a few time series split off from a main trend, they might significantly affect the outline. While such outlying time series could be completely eliminated from the trend-boundary, they are part of the detected (sub)trends. Removing them may significantly underrepresent the range and support of the trend.

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Fig. 18. (a) Overlap of subtrends causes occlusion of subtrends. (b-c) Concurrent different levels of granularity are required to capture all trends. Increasing the granularity causes a collapse of initial trends.

Fig. 17. (a) Initial exploration of the data implies a main trend (b-c) After further refining the search to the upper-/lower-part, two completely separate trends appear that strongly depend on the initial parameterization. (d) Visualizing both trends at the same time gives a complete overview, grouping both trends at the start in a single large trend (3h forecast dew point temperature at 2m in degrees Fahrenheit [EVW] [25]).