Brushing and Linking for Situated Analytics

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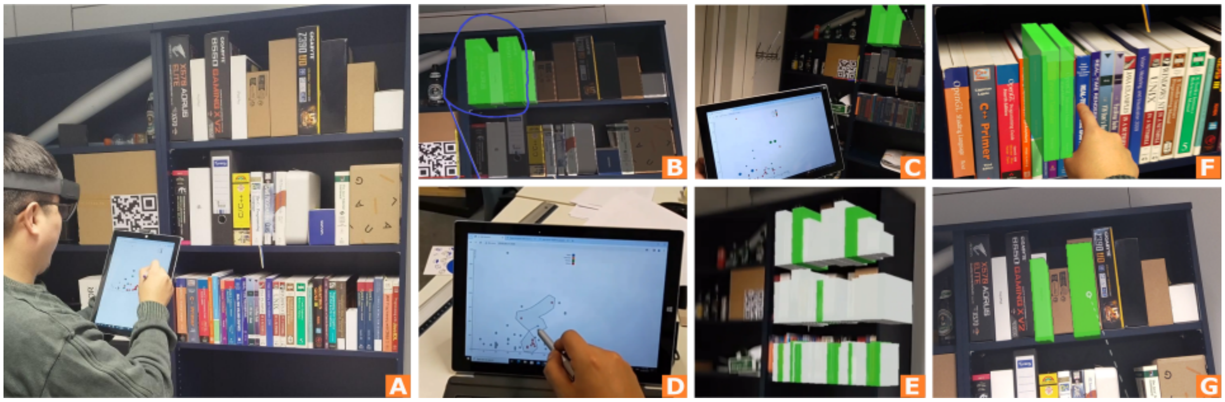

Figure 1: Illustrations of our brushing & linking prototype for situated analytics, where (A) a user browses books in situ using an augmented reality headset and a tablet. (B) To solve analytical tasks, the user wields an AR lasso for brushing books, simultaneously (C) linking to their representative data displayed on the mobile device. The user can also (D) interact with the visualization tool to (E) highlight the books. In addition, (F) touch and (G) ray casting offer useful selection options for different distances.

ABSTRACT

Situated analytics is visual analysis that is embedded in the physical world. Conventionally, the data related to referents (i.e., physical objects) is manipulated indirectly, through dedicated interaction devices or using separate abstract representations. The natural way of interacting in 3D space using direct manipulation with one's hands is hardly employed when abstract data is concerned. In this paper, we explore the idea of directly brushing and linking referents in the real world to analyze abstract data related to the referents. We discuss what *brushing & linking* means when applied to the real world, including multiple ways of selecting referents (*brushing*) in augmented reality, as well as different ways of *linking* with an abstract data view, presented on a dedicated display (a tablet). A proof of concept was implemented to test and demonstrate the capabilities of brushing & linking of referents. We conclude with a set of open research challenges that exist in this new and emerging area.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

1 INTRODUCTION

In this paper, we discuss how the widespread brushing & linking technique for data visualization can be used in situated analytics. In many applications of augmented reality (AR), an important enabling technology is *situated visualization*, that is, showing digital information in the context of the physical environment: AR displays allow situating or embedding the information directly in place with their real-world spatial referents [66]. *Situated analytics* takes this idea one step further and extends situated visualization to analytical scenarios with more complex data and tasks [17, 20].

Historically, interfaces for showing data originate in the area of data visualization. In data visualization, much research has investigated proper representation and interaction concepts. Most data visualization work has concentrated on mouse-and-keyboard setups on the desktop, resulting in techniques that are highly optimized for these environments.

One of the most influential interaction techniques specific to data visualization is *brushing & linking* [2, 5]. In brushing & linking, the user selects and highlights a set of data items in one view (brushing). The selection is then propagated to all other views, in which the same data points are highlighted as well (linking). A typical example is to brush and link data points in a multi-dimensional scatterplot matrix (see Fig. 2a). Another example is linking maps or 3D objects with abstract data, as illustrated in Fig. 2b and Fig. 2c. While much attention has been spent on studying and optimizing brushing & linking for traditional desktop interfaces, there is very little work that seeks to generalize brushing & linking to other display setups [18, 57].

Toward filling this gap, we explore how brushing & linking could be used in situated analytics setups, in which spatial AR displays (e.g., a HoloLens) are combined with 2D data representations (e.g., a hand-held tablet, or an abstract 2D view in AR). We believe that brushing & linking can help to interactively connect *many* physical referents with *complex* abstract visualizations. For example, consider a scenario where a librarian, wearing a head-mounted AR display, inspects a shelf with a selection of currently recommended books. For each book, additional abstract data is available, such as the author, publication year, popularity, etc., shown as scatterplots on a tablet the librarian carries. Brushing & linking across display modalities allows exploration of complex queries. Selecting books on top of the shelf, for instance, might reveal that they tend to be lengthy and rarely requested, and that both of these variables have a

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direct correlation in the data. Of course, such analyses could also be done fully offline in the libarians's office by adding the book positions to the data. However, direct physical actions, such as instantly changing the position of certain books (e.g.,, putting the rarely requested books to the bottom of the shelf), would be separated from the analysis. As such, the main benefit of situated analytics—that is, the tight coupling of physical and analytical actions—would be diminished.

This paper proposes brushing & linking as a new research direction for situated analytics. To illustrate the concept, we built an initial prototype using the HoloLens 2 for spatial interaction and highlighting in AR, and a linked tablet for abstract data visualization and selection thereof. We discuss different design factors and outline the potential benefits of using brushing & linking for situated analytics. To fully exploit these potentials, however, various challenges still need to be overcome. Challenges include, for instance, the efficient selection of multiple physical referents in the spatial environment, proper and consistent highlighting across different display modalities, and the implementation of such distributed hybrid applications. We characterize these and other challenges we have encountered so far, with the aim of guiding further research in this area. In summary, we make the following contributions:

- We propose brushing & linking for situated analytics and discuss the implications of this topic.
- We designed and implemented a prototype for illustration.
- We derive a set of 9 research challenges.

2 BACKGROUND AND RELATED WORK

We provide some background in brushing & linking, and situated analytics, the two areas that we intend to combine in our work. We also discuss the relation of our work to cross-virtuality analytics, an emerging area that shares many of our goals.

2.1 Brushing & Linking

Brushing & linking is a standard technique in data visualization [2,5] and is related to multiple views and their coordination [50,62,64]. Fig. 2 provides examples of brushing & linking in traditional data visualization interfaces. Below, we summarize the main design criteria for brushing & linking and relate them to our goal of using them in situated analytics. For more details on traditional brushing & linking, we point the reader to the recent work by Kyotek et al. [30].

Brushing. Brushing covers the part in which the user *selects* a set of data elements. In 2D interfaces, typical selection mechanisms are rectangular range selections (see Fig. 2a, top row left of the scatterplot matrix) or lasso selections, often combined with logical operators to form more complex queries. Brushing is widely used on conventional desktops using traditional input interfaces (e.g., mouse, touch-pads, touchscreens). In contrast, selecting and brushing a range of objects in the three-dimensional world is challenging, especially when the visualizations are not projected onto a planar 2D surface [11]. Current head-mounted display technologies employ hands, gaze, and eyes as pointing interfaces using direct and ray pointing [39], and efforts have emerged to combine these modalities for efficient 3D manipulation [9,41,42]. For visual analysis tasks, different studies mixed different pointing interactions to solve analytical tasks with 3D visualizations [43,60]. However, the results revealed that such strategies do not cover the need to brush multiple 3D objects, especially when objects are occluded in 3D space.

Linking. The linking part refers to *highlighting* the selected set of points in a consistent manner across multiple data views. Typically, highlighting is done using colors, but other visual features have also been used. Alternatively (or in addition), non-selected points might be visually de-emphasized like in Fig. 2a (non-selected points become small black dots). Care must be taken to ensure that the selected points properly "pop-out" in all the views involved [63]. While visualization interfaces can be designed in a way to perceptually optimize visual highlighting of data points, highlighting physical objects in the real world with AR is a more challenging endeavor, for instance, due to the intrinsic clutter and changing lighting conditions of real environments [13,47].

Variations of brushing & linking. Most brushing & linking approaches use an implicit mechanism to link the data, that is, the user cannot see which data item is exactly linked to which other data item. Linking is done only between sets of items, e.g.,, by coloring all items in the same color. Others have used visual links to provide more explicit linking [61]. Similarly, most brushing & linking methods assume binary selection criteria, that is, an object is selected or not. However, it is also possible to weigh the selections and apply such a complex selection across different views [14] (see Fig. 2). In this paper, we only focus on classical—implicit and binary—brushing, because we consider this a first step to transport these concepts into the realm of situated analytics.

Brushing & linking beyond desktop interfaces. Brushing & linking has also been investigated using other display modalities, such as tabletop displays [28] and large wall-sized displays [32]. Our work goes beyond these non-desktop setups, as we aim at linking across different display modalities. In that sense, the previous works closest to ours are those that investigate cross-modality brushing & linking, such as the work by Langner et al. [33] and Reipschlager et al. [46]. However, these approaches focus only on linking abstract data views across different display modalities. We go one step further and intend to link physical referents in the world with abstract data.

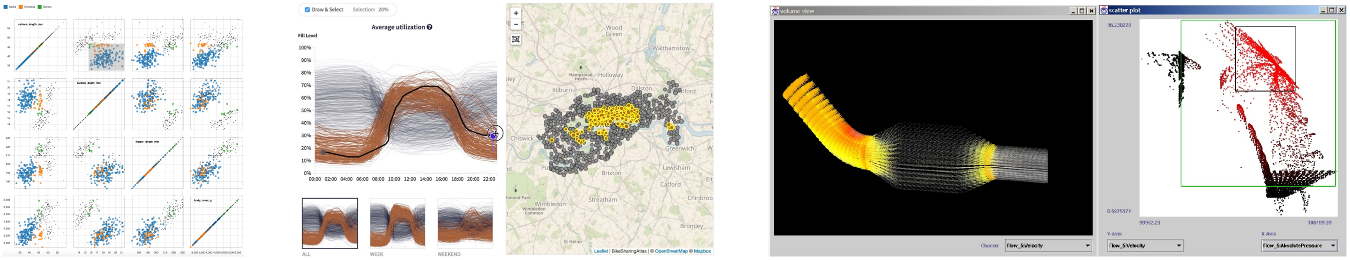
2.2 Situated Analytics

The capacity to solve analytical tasks in physical space has benefits, such as improving sensemaking and obtaining information in a manner that is only possible in situ to improve decision-making [54]. Situated analytics [17] is introduced as the intersection between visual analytics and AR, so that users can perform analytical tasks in context with physical objects (referents). Similarly, Thomas et al. [57] describe the relationship of situated analytics with other fields (e.g., AR, situated visualization, ubiquitous analytics, etc.), discussing opportunities by associating information, manipulating physical objects, and comprehending contextual data. Recently, Shin et al. [53] stated that *"SA is data-driven, uses interactive visualization, is based on Augmented Reality to integrate with the physical environment, draws on the location of the user, and integrates analytical reasoning"*. Moreover, Shin et al. distinguish the related fields based on data, visualization, platform, physical location, and analytics process. They concluded that situated analytics is delivered most coherently using AR technologies. However, AR has its own set of challenges and opportunities, and our proposal looks at how the AR interaction affects brushing & linking.

2.3 Cross-Virtuality Analytics

Visual analytics systems are mature and efficient in analyzing datasets on 2D displays, such as conventional monitors or tablets. Similarly, immersive technologies are able to synergize and complement data exploration [49]. Cross-virtuality analytics (XVA) is a new field that integrates 2D systems and immersive technologies [23]. This field creates new forms of VA employing different visual devices to support multiple users, enabling transitional and collaborative interfaces ranging within different stages of Reality-Virtuality Continuum [38]. Several works on XVR propose asymmetric interaction designs [15,25,58,59,65]. However, these studies in the context of data visualization are limited [48]. Numerous works have explored the augmentation of data mixing AR technologies and 2D surfaces [6–8,22,27,36,46]; however, most of them do not employ physical referents for their analysis.

To summarize, visual analytics and situated analytics are emerging technologies with complementary properties [18]. Consequently,



(a) Scatterplot matrix [55].

(b) Abstract data and a map [40].

(c) 3D object and abstract data [14].

Figure 2: Three examples of brushing & linking in traditional data visualization interfaces. Brushing is done by (a) a rectangular selection box, (b) a range selection through a sketch time-line, and (c) two rectangles to define a weighted distribution of the "level of selection". Linking is done through color in all three approaches.

this paper proposes a brushing & linking approach for the selection of multiple objects and for collaborative XVA.

3 SITUATED BRUSHING & LINKING

As outlined in the literature review, the addition of brushing & linking in situated analytics opens new opportunities for data-centric interaction. Thus, we describe the design goals and illustrate them with an example application.

3.1 Design Goals

Direct Selection of Referents. Humans manipulate objects directly with their hands when standing close to the targets, and, indirectly through instruments (e.g., controllers, voice commands, etc.) when the targets are distant. A natural way to ensure that both data and referents are fluidly accessible [16] relies on embedding and situating views close to the referents [34]. However, this approach usually results in an indirect access pattern, posing the question if faster direct access is feasible. To achieve more direct accessibility, we propose leveraging hand gestures to point to referents and *highlight* them. Implementing this feat is less trivial than it sounds—highlighting 3D models is a recurring topic in computer vision research. Several techniques have been proposed for AR [24], but a gold standard has yet to emerge.

Multi-Scale Selection. It is established that combining existing 3D selection techniques can help to select objects [43, 60]. In 3D, direct touch is usually preferred for near objects [4]. Conversely, casting is not always suitable for distant and small objects, in particular if they are partially occluded. To overcome such limitations, we propose to distinguish different scales of selection as follows:

- **Touch.** The direct manipulation with one's hands is a natural foundation for objects in reach. Although intuitive, a wider range of targets can only be accessed by physically moving through the environment, limiting the technique's scalability.
- **Ray casting.** This technique is based on the colliding of objects using ray pointers [39]. Although using ray pointers is simple and efficient, difficulties arise when the targets are placed at a long distance, because selection requires a high angular accuracy [21]. However, the brushing is more controllable for the user's observable objects.
- **Lasso selection.** Distant objects need a more accurate selection strategy. Inspired by the spatial selection of 3D points [67, 68], we propose a lasso tool for immersive environments. The goal of the lasso tool is to sketch outlines, allowing the user to delimit regions. Therefore, suitable algorithms can be used to project the referent positions onto the planar region. Moreover, we draw inspiration from proxemic interactions [1] and propose a multi-scale selection of referents, governed by the distance and size between referents and user.

Real-time Linking Across Hybrid User Interfaces. Our goal is to combine a head-mounted AR display with a traditional 2D screen, such as a tablet, and brushing & linking should be possible in both directions of this hybrid setup. Previous work has argued that hybrid interface combining immersive and conventional VA technologies can offer a wider range of interaction capabilities without compromising the unique qualities of the combined methods [49]. Hybrid interfaces are also useful for collaborative settings [16] where multiple users employ different interface classes based on their assumed roles in the collaboration.

3.2 Application Case

We have implemented a prototype to test the proposed design choices for brushing & linking in hybrid display setups (AR and tablet)

Browsing objects that are barely visible given their size and distribution is an active area of research [37]. A suitable example is a bookshelf, where books are distributed according to user preferences and the identification of individual book spines is limited due to the small area of the spines. Consequently, several studies have been proposed using overlays displayed on handheld [10, 45] and headworn [44] AR devices.

We select the browsing of physical books as an example application case of brushing & linking. Users can highlight books directly across multiple selection scales, and their selections are reflected in real time in a web application that presents 2D visualizations, as shown in Fig. 1.

We used the HoloLens 2 and the Unity3D game engine (2022.3.7f1) to implement the AR application. Microsoft's Mixed Reality Toolkit (version 3) was used for spatial interactions. For highlighting, we designed three-dimensional shapes with the same object dimensions and positioned them in the object location. The virtual objects have a binary state (selected or unselected); they are shown in green color when selected. The following simple heuristic was found to be sufficient for implementing the lasso tool: First, the front plane of the bookshelf was indicated using a QR code. Then, the vertices of the book's bounding box were projected into this plane. If a minimum number of vertices belonging to a book lies inside the lasso area, the book is selected. Using WebSockets, the selection is distributed across the displays, i.e., the HoloLens and a tablet. The tablet runs a simple web application showing a scatterplot using D3 [3].

4 DISCUSSION

In the following, we discuss our preliminary observations on the topic and outline various challenges and opportunities.

4.1 Brushing in the Physical World

Input modalities for brushing. Traditional brushing & linking for visualization predominantly uses indirect 2D pointing devices (i.e., mouse) or, in the case of tablets or smartphones, touch input. Touch or ray casting gestures can sometimes be difficult to perform, either due to fatigue, imprecision [21], or poor scalability in the presence of hidden or densely spaced referents [34]. Other selection techniques could better support situated brushing & linking, by employing alternative modalities (e.g., eye gaze, voice commands) or relying on proxy representations of the referents, such as a world in miniature [52].

Context-aware selections in information-rich environments. Unlike desktops which offer a predictably consistent display canvas for visualisation, AR needs to consider the physical context. For example, a voice command that selects "all objects in the top-right corner" is dependent on the user's viewpoint. Even for gesture-based selections, awareness of the user's surroundings is required to correctly interpret the user input. For example, objects that are occluded from the user's present point of view should be excluded from selection even if they are contained in a lasso selection.

Moreover, physical environments can oftentimes be densely filled with information, at a much larger quantity and variety than the user may care about. Consider, for example, a library that consists mainly of books, but also newspapers, discs, and even desktop workstations or printers. The user may want to analyze—and therefore select—just certain object types. Filtering by type could either be explicitly expressed by the user or inferred automatically by the system based on the user's actions. Objects can also be subject to a hierarchical categorization, which the user may want to employ in the analysis. For instance, rather than selecting by book, a user might want to select by *section*, *division*, or even *class* (as per the Dewey Decimal Classification) of books. Handling such abstract semantic categories, both in terms of situated visualization and situated interaction, is a problem open for investigation.

4.2 Linking the physical world

Real vs. abstract highlighting of the object. While highlighting in desktop brushing & linking focuses on the usage of common pop-out effects (e.g., changing the color of a dot [63]), research of attention guidance in AR investigates approaches that increase immersion and sense of presence [13, 31]. The research question of how to best achieve the highlighting of a target remains at least partially open. Is it enough to highlight the target objects with generic approaches like color, or is it necessary that these links fit into the current environment? Assuming color is used, we should further investigate how and which color can be applied. Some colors may not be beneficial in some contexts due to changing lighting or background conditions. If highlighting techniques are designed to match the scene, it might be interesting to study whether these techniques still stand out enough to let the user quickly process them as links between views or instances.

Recognition and obtrusiveness of the actual highlighted object. As depicted in Fig. 1, the referents (books) are highlighted with solid colors of white and green. Such a visually pronounced overlay makes it difficult to observe details such as the title or author physically written on the book. For some use cases, such physical details may be negligible. Alas, for most of the use cases, such as finding a certain referent among many similar ones, the details (and the real world in general) must remain recognizable. In a similar manner, we should also consider how much highlighting is actually necessary. Every visual addition diminishes the user's perception of reality, leading to increased clutter and cognitive load. Conversely, an overly subtle highlighting might be overlooked. It might also be necessary to consider whether a certain way of highlighting leads to visual clutter and an increase in cognitive load. Hence, the highlighting techniques must, at the very least, be adaptable (or, ideally, automatically adapting) to ensure an appropriate perceptual situation for the user.

Highlighting many objects simultaneously. Traditional brushing & linking applications require the selection and highlighting of subsets that include more than one object. Such multi-object selection is uncommon in AR, where most applications concentrate on a single physical artifact or location. A scalable version of highlighting that supports multi-referent brushing cannot rely on conventional approaches, such as merely applying color, as changing the appearance of many physical objects in an uncontrolled manner may easily result in visual clutter. Currently, we have a poor understanding of this problem, as most research on immersive highlighting (or other attention guidance techniques) focused on the evaluation of effective highlighting for one target at a time [13, 47]. The scalability of immersive highlighting techniques in visually dense environments remains largely unexplored.

Influence of physical world background on highlighting While the previous challenges focus more on the visual properties of the elements to be highlighted, the background of the physical environment clearly has importance as well. Both the intensity of the highlighting and the recognition of the original referent are strongly contingent upon the background environment. Very much unlike traditional desktop visualization, the appearance of a physical background is usually out of control of the AR system. A particular highlighting technique may, therefore, properly pop out in some situations, while being incomprehensive in others. For example, a green text over a white background may be readable, while the same green text over a green background may not. Moreover, the user's continuous change of viewpoint makes it difficult to optimize appearance, as the view-dependent background is constantly changing [29].

4.3 Joint challenges for brushing and linking

Fully exploring the design space and interplay of brushing & linking for situated analytics. Whilst this section has addressed *brushing* and *linking* as two independent components, it is their combined effectiveness that should ultimately be considered. Optimizing each one individually is still a worthwhile endeavor, but certain combinations may ultimately be incompatible. For example, consider a ray casting technique for brushing used in conjunction with straight visual links—the presence of a large number of similar-looking lines may cause too much clutter and distraction for both to be usable together. Thus, this holistic exploration into the design of situated brushing & linking, similar to traditional brushing & linking [30], along both facets is clearly necessary. We once again note that the context (e.g., composition of physical objects, physical background, task) plays a significant role in whether certain combinations prove practical or not. As a simple example, a touch-based selection technique using simple color highlighting may be practical for a handful of physical objects, but become impractical when dealing with many objects. A user-customizable approach similar to MyBrush [30] may be beneficial in such a situation.

Design consistency of bidirectional brushing and linking. The novelty of situated brushing & linking lies in connecting the real physical world with abstract data. One direction is to brush real-world objects as a source, which then links to data marks on a virtual visualization. The other way is to brush on a virtual visualization (displayed, for example, on a physical tablet or floating panel), and link it to real-world objects. Many traditional brushing & linking techniques, particularly brushing, can be employed to facilitate this direction (e.g., a pen lasso as shown in Fig. 1). To support fully symmetrical analysis across both physical and virtual views, bidirectional brushing & linking needs to be considered (i.e., from physical to virtual, and from virtual to physical). With this in mind, interaction or highlighting paradigms which are inconsistent across directions would confuse the user. For example, a 2D selection involving pen input would be inconsistent with a 3D selection involving eye gaze. Therefore, finding a middle ground might be necessary to ensure intuitive brushing & linking in both directions, whilst still leveraging the capabilities of both environments. A possible approach to overcome this inconsistency is to focus on the pointer encoding. We speculate that real-time visual cues across platforms would provide visual selection awareness similar to virtual reality environments [59]. Additionally, from our application case, we identified that the proximity of real objects offers indirect zooming, which is a common standard in 2D desktop interfaces. For that reason, we consider zooming an important new addition to in-situ brushing & linking.

Supporting visual comparisons across referents and visualizations. Once a selection has been made, and the corresponding elements highlighted (i.e., linked), the user makes visual comparisons between the multiple views. In traditional visualization, much research has sought to support this comparison, such as by synchronizing color or stroke changes [30], employing context-preserving visual links to connect elements [56] or even repositioning and aligning visualization planes in 3D space for more favorable viewing angles [12]. In AR, a one-to-one translation of the aforementioned approaches may prove inadequate. For instance, a simple color change does not benefit from the pre-attentive "pop-out" effect [26] if referent or visualization are visually obscured (or otherwise out of view), since the user would not be able to notice them. A visual link that indicates that objects are out of view may still be cumbersome if the links are too lengthy or visually cluttered [35]. It is possible that some method of manipulating referents and visualizations in AR can overcome these issues. For example, adaptively repositioning a visualization [19] can reduce the gap by making referent and visualization more spatially juxtaposed. Alternatively, the physical scene can be visually compressed [51] or virtually replicated at a smaller scale [52]. Which of these directions scales well in complex scenarios remains to be investigated.

5 CONCLUSIONS

Motivated by situated analytics [53] and the need to integrate different environment settings [23], this paper proposes a multimodal interaction design to enable brushing & linking in AR. Unlike previous work, our design choices include referent selection without dependency on external interfaces, multi-scale alternatives for near and far selection, and a hybrid user interface incorporating traditional 2D visual analytics. An example application case was implemented for browsing physical objects, demonstrating the affordability of our proposal. Furthermore, we discussed challenges and opportunities of future methods for brushing & linking in situated analytics.

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