Development of Indexes for the Form and Layout Design of Urban Residential Settlements in the West Plateau Region of China

Yu Liu[1], Yi Liu[1], Jin Wang[1], Wuxing Zheng[1], Teng Shao[1], Shangkai Hao[1], David Hou Chi Chow[2], Jingtao Du[2]

[1]Sustainable Building and Environmental Research Institute/Northwestern Polytechnical University, Xi'an (China)

[2] School of Architecture /University of Liverpool, Liverpool (U.K.)

Abstract

Solar radiation is the most important climate resource for human being. In order to achieve full acquisition and optimal distribution of solar radiation in urban residential settlements (URS), it is considered necessary to guide and control the form and layout design of URS. This research was conducted targeting URS in the west plateau region of China, which possesses abundant solar radiation resource. Firstly, web-based and on-site investigations were conducted, based on which typical building types and layout forms of URS in three representative cities in the researched region, as well as dimensions of typical residential buildings in such URS were identified, some living habits and needs of local residents in the researched region in wintertime were observed and recognized. Secondly, through software simulations, a number of different orientations, typical layout forms and sub-forms of URS were compared regarding their potential of solar radiation acquisition, based on which four indexes are proposed for guiding the design of URS in Lanzhou city. Finally, conclusions and limitations of the research are provided, and further researches are recommended.

Key-words: urban residential settlements (URS), form, layout, design, index, west plateau region, China

1. Introduction

The form and layout of urban residential settlements (URS) have a decisive influence on their potential accessibility to regional climate resources, including solar radiation resource. Design indexes are important in terms of guiding and control the direction of design. So far, few researches have been conducted to develop guiding and or control indexes for the form and layout design of URS concerning their potential of solar radiation acquisition. Supported by some national and provincial funded projects, a series of researches were conducted targeting URS in the west plateau region, which is also a solar resource intensive region, of China. Purpose of the research was to develop guiding indexes for the form and layout design of URS, in order to maximize their potential of solar radiation acquisition. Some results of the research are introduced in this paper.

2. A brief literature review

2.1. Overview

The accessibility of solar radiation in the high density urban areas (including URS) has attracted increasingly more interests of research worldwide in the last 20 years (Lundgren and Dahlberg, 2018, Hachem-Vermette and Singh, 2019, Hachem et al., 2012). A search of literature between 1999 and 2019 on the *Web of Science* database on the topic of community and solar energy shows a result of 3991 records with clear trend of continuous rise; while a similar search on CNKI, a Chinese literature database, shows a results of 179 records during the same period of time with no obvious trend, which implies a possible insufficiency of such research in China so far. (Fig. 1)

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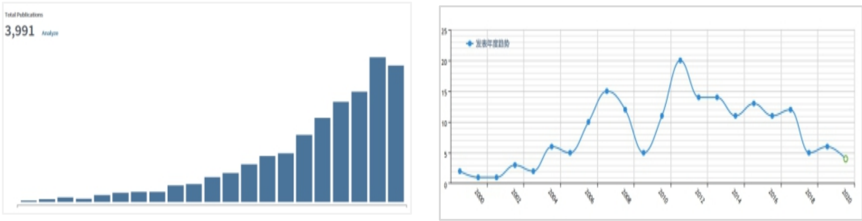


Fig. 1 Results of literature search on the topic of "community AND solar energy" (1999-2019)

Source：(left) Web of Science database; (right) CNKI database

2.2. Indexes in the existing standards in China

In the existing design standards in China, there are two types of guiding or control indexes that are directly related to the utilization or acquisition of solar radiation: type A. performance index, type B. design index. Examples of type A index include sunshine hours, sunshine effectiveness, solar radiation absorption rate of decorative materials, calculated temperature in passive solar heating room, daylight factor, shading coefficient, solar radiation correction coefficient, shading coefficient, solar radiation correction coefficient, etc. Examples of the type B index include coefficient of sunshine spacing, window to wall ratio, orientation of attached solar space, pitch of roof, proportion of the area of shading facilities against that of the transparent part of the exterior windows, etc. (Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), 2012) (Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), 2018) Overall, there are more Type A indexes, less Type B indexes. Most existing indexes are established at individual building scale and few at the residential community scale. This research intends to develop new Type B indexes for the form and layout design of URS in the west plateau region of China.

3. Investigations on URS in the west plateau region of China

A series of investigations were conducted targeting URS in three representative cities (Lanzhou, Xining and Lhasa) in the researched region. Some basic information of the three cities is listed in Tab. 1.

Tab. 1 Basic information of Lanzhou, Xining and Lhasa (Data source: SOLARGIS, http://solargis.cn)

	Lanzhou	**Xining**	**Lhasa**
latitudes	36.04	36.49	29.39
longitude	103.45	101.26	91.07
altitude（m）	1543	2697	3654
solar radiation (direct normal) (MJ/m^2Y)	4705	5526	9147
air temperature(yearly) (°C)	9.5	3.3	4.2

3.1. Web-based investigation

A number of digital map tools first compared, among which OpenStreetMap-OSM and Baidu Map were first identified as the ones that can meet the basic needs of the research. With a real scene function and possibility to check the height of buildings, Baidu Map was further utilized to identify the layout forms of URS and types of residential building in URS in Lanzhou, Lhasa and Xining.

1) Lanzhou city

Lanzhou is located on the Loess plateau, between two mountains, with the Yellow River running through the city. Web-based investigation in Lanzhou involved identification of typical forms of URS in the city area, as well as typical building types in the URS.

A total of 264 URS were identified on the digital map, in which 43 are mainly composed of *tower-type* buildings, 44 are composed of *plank-type* buildings, and 177 are composed of a mix of *tower & plank-type* buildings (in China, *tower-type* building refers to high-rise buildings that possess similar size of depth and width, which make them looked like towers, *plank-type* building refer to roughly cubic form buildings that possess a relatively small depth and larger width, which make them looked somewhat like planks; high-rise residential building refers to residential buildings that possess a height greater than 27m). Layout of the identified typical URS are mainly arranged in 3 different forms: *row, enclosed* and *fan. Row* refers a form of URS in which buildings are arranged largely in a range of rows; *enclosed* refers to a form of URS in which some buildings are arranged along the edge of the site, so form an enclosed or semi-enclose feeling of space inside the URS; *fan* refers to a form of URS in which buildings are arranged in a fan shape. *Row* and *enclosed* are the major forms in Lanzhou, while *fan* is a form that can suit special site conditions and it is not usually found in other cities. (see Fig. 2-3, Tab. 2-3)

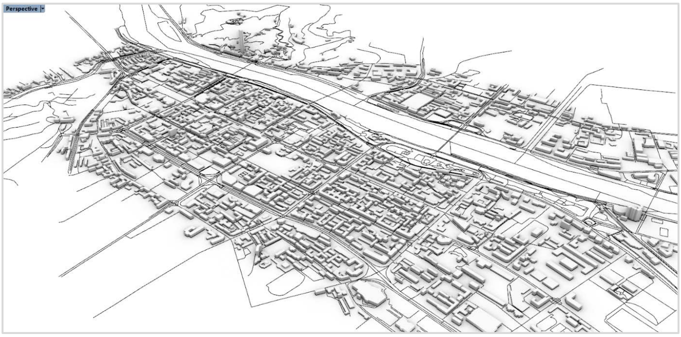


Fig. 2 Map of the dense urban area of Lanzhou city (source：OpenStreetMap-OSM, edited by Yi Liu)

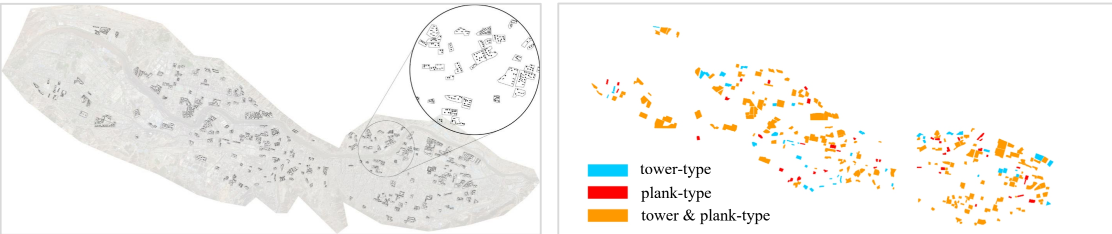


Fig. 3 Distribution of different types of URS in the dense city area of Lanzhou (source: Baidu Map, edited by Yi Liu)

2) Lhasa city

Lhasa is located on the Qinghai-Tibet plateau. Web-based investigation reveals that, layouts of URS in Lhasa are mainly arranged in 2 forms: *row* and *enclosed*, with the first one be the dominant form.

Two distinguished building styles are identified in Lhasa: *local* style and *inland* style. *Local* style refers to a kind of low-rise buildings evolved locally in Lhasa region. They are built with courtyards and their functional arrangement express a kind of traditional features in the Tibetan region. *Inland* style refers to the mid-rise and high-rise buildings without courtyards. Their functional layouts are largely the same as normal buildings in most inland cities in China, but their colors, symbols and decorations more or less possess clear local features. URS with *inland* style residential buildings can be further divided into three types: *plank, towe*r, and a mix of *tower & plank*, with the first one be the dominant type.

3) Xining city

Xining is also located on the Qinghai-Xizang plateau, north-east to Lhasa. Web-based investigation reveals that, URS in Xining are mainly arranged in two forms: *row* and *enclosed*, with the first be the dominant one. Residential buildings in the URS in Xining can be divided into three types: *plank*, *tower*, and a mix of *plank & tower*, also with the first be the dominant one.

A summary of building types and URS forms identified through web-based investigation is shown in Tab. 2.

Tab. 2 Building types and URS forms

Cities		Building types		
Lanzhou		high-rise/plank *	high-rise/tower	high-rise/tower & plank
Lhasa	Inland style	mid-rise/plank* high-rise/plank	high-rise/tower	mid/high-rise/tower & plank
	Local	low-rise/plank with courtyard		

style			
Xining	high-rise/plank *	high-rise/tower	high-rise/tower & plank

Cities	**URS forms**		
Lanzhou	row *	enclosed	fan
Lhasa	row *	enclosed	/
Xining	row *	enclosed	/

Note: * the dominant one

3.2. On-site investigation

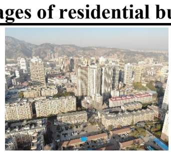
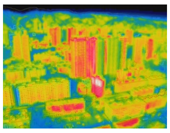
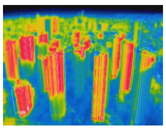
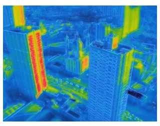
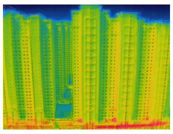
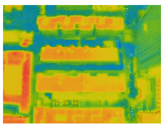
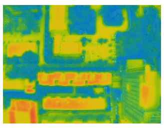
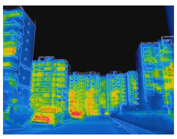
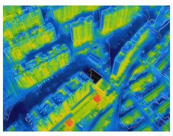
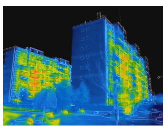
1) Dimensions of buildings

On-site investigations show that, in Lanzhou city, the *plank* type residential buildings in URS usually possess a surface width of about 30 meters. When two buildings are placed side by side, the maximum width can reach 60 meters. The depth varies from about 14 to 30 meters. The width-to-depth ratio of a *tower* type building is usually about 1.45, while that of a *plank* type building with one unit is about 2.0, with two or more than two units is about 3.5, and maximum 4.61. In the newly constructed URS, building spacing all meet building standards for solar access; however, in the old ones, the space between buildings are obviously smaller.

2) Solar radiation on building surface

To reveal influence of direct solar radiation on building surfaces, infrared thermal image of facades and roofs of buildings inside URS in Lanzhou, Xining and Lhasa cities were collected by a small UAV with thermal infrared camera. The results show that solar radiation have obvious effect on the surface of buildings. A clear boundary line can be identified between the shaded and unshaded areas. The temperatures of external surface of buildings in areas with direct solar radiation are significantly higher than those in the shaded areas. Besides, orientations of buildings have a clear effect on their external surface temperatures. (see Tab.3)

Tab. 3 Thermal images of residential buildings in the researched region

Lanzhou (Jun.2019)	Photo			
	Thermal image			
Xining (Jun.2020)	Photo			
	Thermal image			
Lhasa (Jan.2020)	Photo			
	Thermal image			

3) Living habits of local residents

On-site observations in URS in the researched region show that, “get out in the sun” in the warm and sunny days of wintertime is a common desire and even habit of many local residents . This is applicable for people of all ages and especially for the elderly, which implies a practical significance to maximize the wintertime solar radiation receiving potential of URS in the researched region.

4. Indexes for the form and layout design of URS

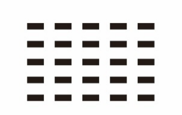
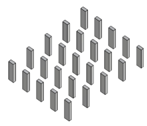
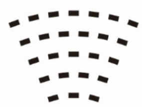
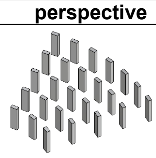
4.1 Orientation of URS

URS in Lanzhou city are taken as examples in the following simulation and discussion.

1) Model setting

According to the results of above-mentioned investigations, *row* and *fan* forms were selected to establish typical models of URS for further discussion. Setting of the models was the following: 25 individual buildings each with a dimension of 30m*15m*80m; the building cluster with a north-south spacing of 75m, and a gable spacing of 40m. All the settings meet the basic requirements of national and regional design standards for URS and residential buildings regarding solar access in winter time. (see Tab.4)

Tab. 4 Models of two typical layout forms of URS

Row		Fan	
plan	perspective	plan	perspective
			

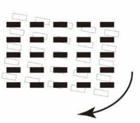
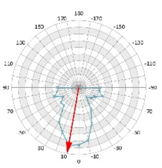
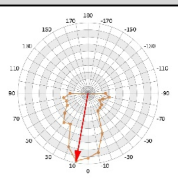
2) Results of simulation

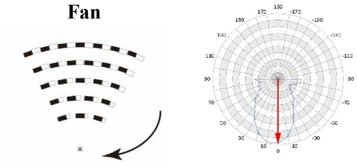
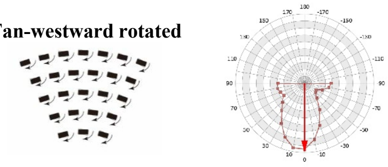
Rhino's ladybug plugin was applied for the simulation. According to the *Technical Specification for Passive Solar Buildings* (DB62/T25-3079-2014), a regional building standard of Gansu Province, in which Lanzhou city is its capital city, the simulation period was set the same as its public heating period: from November 2 to March 14 of the following year, a total of 132 days. The total rotation angle of orientation was set at 360° and the step length of change was set at 10°.

Results of the simulations show that, in terms of solar radiation receiving potential, the optimal orientation of *row* forms is 10° south by west, while that of *fan* forms is south. For different orientations of *fan* forms, the difference of radiation level between south and 10° south by west orientation is very small. On the whole, the simulated results show a rough southward advantage, with southwest being slightly better than southeast orientation. (see Tab.5)

Therefore, from the perspective of solar radiation receiving potential, a guiding index for the orientation design of URS in Lanzhou is recommended as: Index ①--the percentage of orientation that is between *south* and *10° south by west*. A higher percentage means better solar radiation receiving potential, so should be encouraged.

Tab. 5 Optimal orientations of URS

Forms of URS	Optimal orientation		Forms of URS	Optimal orientation	
Row 		10° south by west	**Row-westward rotated** 		10° south by west

Fan		Fan-westward rotated	
	south		south

Note: red arrows indicate the optimal orientation for the best potential access to solar radiation

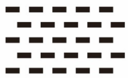
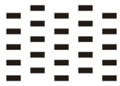
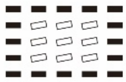
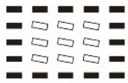
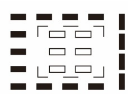
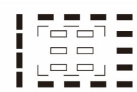
4.2 Layout of URS

1) Model setting

As mentioned before, typical layout of URS in Lanzhou can be classified into three forms: *row*, *enclosed* and *fan*. Considering that the overall layout of Lanzhou is related to the trend of the Yellow River that passes through the city, and the fact that many existing buildings in the city are set at 30° perpendicular to or parallel to the course of the river, an angle of 30° were set for the rotated sub-forms of URS.

For comparative purpose, different layout forms of URS in the simulation model were all set as a cluster of 25 buildings, in which 16 at surrounding positions and 9 at internal positions. Overall, 13 sub-forms of layout were established for simulation analysis. (see Tab.6)

Tab. 6 Forms and sub-forms of URS for simulation

Forms	Sub-forms		
Row			
	No.**1** regular	No.**2** horizontally staggered	No.**3** vertically staggered
			
	No.**4** eastward rotated		No.**5** westward rotated
			
	No.**6** inner part eastward rotated		No.**7** inner part westward rotated
Enclosed			
	No.**8** with 1 row of east-west facing building at the east side	No.**9** with 1 row of east-west facing building each at the east and the west side	No.**10** with 1 row of east-west facing building at the west side
Fan			
	No.**11** regular	No.**12** westward rotated	No.**13** eastward rotated

2) Results of simulation

Regarding solar receiving potential per unit building construction area, *Row* form in whole is higher than the other two forms. Among the 13 sub-forms, *Row-regular* form (No.1) is the highest, closely followed by *Row-inner part westward rotated* (No.7), *Row-inner part eastward rotated* (No.6), and *Row-westward rotated* forms (No.5); *Fan-eastward rotated* form is the lowest (No.13), followed by *Fan-westward rotated* form (No.12) (see Fig. 4 left)

Regarding solar radiation receiving potential per unit land area, *Fan-regular* form (No.11) is the highest, followed by *Row-regular* (No.1), *Row-inner part westward rotated* (No.7), *Row-westward rotated* (No.5) and *Row-inner part eastward rotated* forms(No.6); *Row-vertical staggered* from (No.3) is the lowest, followed by the three *Enclosed* sub-forms (No. 9, 8/10). (see Fig. 4 right)

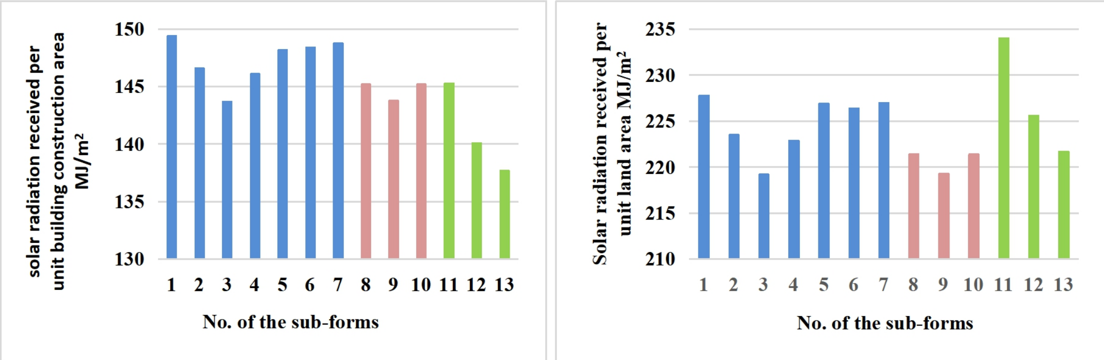


Fig. 4 Left: solar radiation received per unit building construction area（MJ/m²）; Right: solar radiation received per unit land area（MJ/m²）

Priorities of the sub-forms of URS regarding their solar radiation receiving potential per unit building construction area and per unit land area are listed in Tab.7.

Tab. 7 Priorities of the sub-forms of URS regarding their solar radiation receiving potential

Priorities	**Sub-forms of URS**	
	Solar radiation receiving potential per unit building construction area	**Solar radiation receiving potential per unit land area**
1	No.1 **Row**-regular	No.11 **Fan**-regular
2	No.7 **Row**-inner part westward rotated	No.1 **Row**-regular
3	No.6 **Row**-Inner part eastward rotated	No.7 **Row**-inner part westward rotated
4	No.5 **Row**-westward rotated	No.5 **Row**-westward rotated
5	No.2 **Row**- horizontally staggered	No.6 **Row**-inner part eastward rotated
6	No.4 **Row**-eastward rotated	No.12 **Fan**-westward rotated
7	No.11 **Fan**-regular	No.2 **Row**-horizontally staggered
8	No.10 **Enclosed**-with 1 row of east-west facing building at the west side No.8 **Enclosed**-with 1 row of east-west facing building at the east side	No.4 **Row**-eastward rotated
9	No.9 **Enclosed**-with 1 row of east-west facing building each at the east and the west side	No.13 **Fan**-eastward rotated
10	No.3 **Row**-vertically staggered	No.10 **Enclosed**-with 1 row of east-west facing building at the west side No.8 **Enclosed**-with 1 row of east-west facing building at the east side
11	No.12 **Fan**-westward rotated	No.9 **Enclosed**-with 1 row of east-west facing building each at the east and the west side
12	No.13 **Fan**-eastward rotated	No.3 **Row**-vertically staggered

Accordingly, four tentative indexes for the layout design of URS in Lanzhou are recommended as the following:

Index ②--the percentage of building construction area in the URS that is arranged in any of the following layout forms: *Row-regular* (No.1)*, Row-inner part westward rotated* (No.7), *Row-inner part eastward rotated* (No.6).

Index ③--the percentage of building construction area in the URS that is arranged in any of the following layout forms: *Fan-eastward rotated* (No.13)*, Fan-westward rotated* (No.12), *Row-vertically staggered* (No.3).

Index ④--the percentage of land area in URS that is arranged in any of the following layout forms: *Fan-regular* (No.11), *Row-regular* (No.1), *Row-inner part westward rotated* (No.7).

Index ⑤--the percentage of land area in URS that is arranged in any of the following layout forms: *Row-vertically staggered* (No.3), any of the three *Enclosed* form (No.9, 8/10).

For indexes ② and ④, a higher percentage means better solar radiation receiving potential, so should be encouraged; while for indexes ③and ⑤, a higher percentage means worse solar radiation receiving potential, so should be avoided when possible.

5. Conclusions, limitations and further researches

5.1 Conclusions

The building types and layout forms of URS in three typical cities (Lanzhou, Xining and Lhasa) in the west plateau region of China are discussed based on web-based investigations, on-site investigations and software simulations. Three typical building types (*plank*, *tower* and a mix of *plank & tower)*, as well as three typical layout forms (*row*, *enclosed* and *fan*) of URS were first identified in the investigated cities.

Simulations were then run targeting one dominant building type (high-rise/plank), two typical layout forms (*row* and *fan*) and thirteen sub-forms of URS that had been identified in Lanzhou city, based on the results of which five tentative indexes for guiding the form and layout design of URS were proposed as the following:

- ✧ Index ①--the percentage of orientation of buildings in URS that is between *south* and *10° south by west*.
- ✧ Index ②--the percentage of building construction area in URS that are arranged in any of the following layout forms: *Row-regular* (No.1)*, Row-inner part westward rotated* (No.7), *Row-inner part eastward rotated* (No.6).
- ✧ Index ③--the percentage of building construction area in URS that are arranged in any of the following layout forms: *Fan-eastward rotated* (No.13)*, Fan-westward rotated* (No.12), *Row-vertically staggered* (No.3).
- ✧ Index ④--the percentage of land area in URS that is arranged in any of the following layout forms: *Fan-regular* (No.11), *Row-regular* (No.1), *Row-inner part westward rotated* (No.7).
- ✧ Index ⑤--the percentage of land area in URS that is arranged in any of the following layout forms: *Row-vertically staggered* (No.3), any of the three *Enclosed* form (No.4-6).

For indexes ①, ②and ④, a higher percentage means better solar radiation receiving potential, so should be encouraged; while for indexes ③and ⑤, a higher percentage means worse solar radiation receiving potential, so should be avoided when possible.

5.2 Limitations and further researches

Limitations of this research mainly lie in four aspects: first, the simulation models, although were established based on statistical analysis of investigations, were highly abstracted and simplified, so could not fully reflect the complex conditions of URS in the real world; second, the proposed indexes were developed largely based on software simulations, the results of which have not yet been fully validated; third, the simulations were conducted only targeting URS in Lanzhou city, it is not yet clear if similar results could be achieved in other typical cities in the researched region; fourth, the practicability of the proposed indexes have not yet been tested.

Accordingly, further researches are recommended to: firstly, validate the simulation results by on-site surveys and measurements, etc.; secondly, conduct same researches in other typical cities in the researched region (e.g. Xining and Lhasa) to see if similar results could be achieved; and thirdly, apply the proposed indexes in real design practices to test their practicability, and base on which to adjust, deepen, or improve them when possible.

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