INTRODUCTION

Unique honeycomb orbital symmetry underlies the unusual properties of two-dimensional (2D) single hexagonal structures, such as graphene,1–3 silicene and group III–IV binary compounds. Moreover, quasi 1D nanoribbons and flakes of these 2D layers have added interesting electronic and magnetic properties, which are expected to give rise to important future applications in nanotechnology.4–9 Recently, 2D suspended single layer molybdenum disulﬁde, MoS2 sheets with honeycomb structure have been produced.10,11 Single layer MoS2 nanocrystals of ∼30 Å width were also synthesized on the Au(111) surface and its direct real space STM have been reported.12 Unlike graphite and hexagonal BN, the layers of MoS2 are made of hexagons with Mo and S atoms situated at alternating corners. Apparently, 3D graphic bulk structure called 2H-MoS2, 2D single layer called 1H-MoS2, quasi 1D nanotubes13 and nanoribbons of MoS2 share the honeycomb structure and are expected to display interesting dimensionality effects.

Properties of MoS2 nanocrystals are explored in diverse fields, such as nanotribology,14,15 hydrogen production,16,17 hydrodesulfurization catalyst used for removing sulfur compounds from oil,18–24 solar cells,25 and photocatalysis.26 Triangular MoS2 nanocrystals were obtained as a function of size by using atom-resolved scanning tunneling microscopy.27 Photoluminescence emerging from 1H-MoS2 was observed.28 Superlow friction between surfaces coated with 1H-MoS2 has been measured much recently.15 Using electrochemical methods micro and nanoribbons have been synthesized from crystalline 2H-MoS2.29 Various properties of 2H-MoS2 (see refs 30–45), 1H-MoS2 (see refs 13, 44, and 46–50), and its nanoribbons (see refs 44 and 48) have been an active subject of theoretical studies.

In this paper, we present our systematic theoretical investigation of optimized atomic structure and phonon spectrum, mechanical, electronic, magnetic properties of armchair (A-MoS2 NR) and zigzag (Z-MoS2 NR) nanoribbons. Our study reveals interesting results, which are important for further study and applications of these nanoribbons. These are as follows: (i) We demonstrated the stability of MoS2 nanoribbons through first-principles calculations of phonon frequencies. Specifically we deduced the branch of twisting modes. (ii) We calculated force constants and in-plane stiffness of armchair and zigzag nanoribbons showing that they are stiff materials. (iii) We examined the effects of the reconstruction of edge atoms and their passivation by hydrogen on the electronic and magnetic properties of nanoribbons. The energy is optimized through a (2 × 1) reconstruction of edge atoms and their passivation by hydrogen on the electronic and magnetic properties of nanoribbons. (iv) The properties of MoS2 nanoribbons can be dramatically modified by foreign atom adsorption and vacancy defects. Since recent works15,17,34 show that single layer MoS2 flakes as large as 200 μm2 can now be produced and also can be characterized, present results are crucial for further research on MoS2 nanoribbons.
METHODS

Our results are based on first-principles plane wave calculations within density functional theory (DFT) using projector augmented wave (PAW) potentials. The exchange correlation functional is approximated by generalized gradient approximation (GGA) using PW91 functional both for spin-polarized and spin-unpolarized cases. All structures are treated using the periodic boundary conditions. Kinetic energy cutoff, and Brillouin zone (BZ) sampling are determined after extensive convergence analysis. A large spacing of ~10 Å between the S planes of two MoS2 layer are taken to prevent interactions. A plane-wave basis set with kinetic energy cutoff of 600 eV is used. In the self-consistent field potential and total energy calculations BZ is sampled by special k-points by using the Monkhorst—Pack scheme. For nanoribbons, BZ is sampled by 1 × 1 × 9 k-points. All atomic positions and lattice constants are optimized by using the conjugate gradient method, where the total energy and atomic forces are minimized. The convergence for energy is chosen as 10^-5 eV between two consecutive steps, and the maximum Hellmann—Feynman forces acting on each atom is less than 0.05 eV/A upon ionic relaxation. The pressure in the unit cell is kept below 1 kBar. The phonon dispersion curves are calculated along symmetry directions of BZ within density functional theory using the small displacement method (SDM). Numerical calculations have been performed by using VASP. Bader analysis is used for calculating the charge on adatoms.

PROPERTIES OF TWO DIMENSIONAL MoS2

For the sake of comparison we first present a brief discussion of the properties of 2D 1H-MoS2 calculated with the same parameters used for quasi 1D nanoribbons. Single layer MoS2 structure consists of monatomic Mo plane having a 2D hexagonal lattice, which is sandwiched between two monatomic S planes having the same 2D hexagonal lattice. Mo and S2 occupy alternating corners of hexagons of honeycomb structure. The contour plots of calculated charge density and difference charge density isosurfaces clarify the charge distribution in layers of MoS2 structure. Electronic charge transferred from Mo to S atoms gives rise to an excess charge of 0.205 electrons around S atoms giving rise to an excess charge of 0.205 electrons around S atoms. The ground state of monolayer 1H-MoS2 is nonmagnetic semiconductor having direct band gap of 1.58 eV. The lengths of Mo—S, S—S, and Mo—Mo bonds are 1.70 and 1.36 Å, respectively. The distance between S atoms at the edge is calculated as 3.27 Å upon hydrogen passivation.

Phonon Calculations, Stability, and Elastic Properties. While the structure optimization through energy minimization yields an indication whether a given nanoribbon is stable, a rigorous test for the stability can be achieved through phonon calculations. If the calculated frequencies of specific phonon modes are imaginary, the structure becomes unstable for the corresponding k-wave vectors in the BZ. Here we present an example for the stability test of nanoribbons, whereby we calculate the phonon frequencies of the bare armchair nanoribbon with n = 12. The calculated phonon branches and corresponding density of states (DOS) are presented in Figure 1. The out of plane (ZA) branch with parabolic dispersion and fourth acoustic branch (or twisting mode) characteristics of nanoribbons are obtained. Earlier, the branch of twisting mode was revealed in MoS2 nanotubes. Similar twisting modes are also calculated for ZnO nanoribbons. The overall shape of DOS of nanoribbons is similar to that of 2D MoS2 sheets, except that the gap between optical and acoustical branches is reduced due to edge phonon states. For the same reason additional peaks occur for flat phonon branches of edge modes in band continua. All modes significant changes in the properties of the nanoribbons. In this respect, one expects that the armchair (A-MoS2NR) and zigzag (Z-MoS2NR) nanoribbons of 1H-MoS2 can display even more interesting electronic and magnetic properties.

1D MoS2 NANORIBBONS

Two dimensional 1H-MoS2 can maintain its physical properties, when its size is large. However a small flake or a ribbon can display rather different electronic and magnetic properties. In particular, edge atoms may influence the physical properties. The passivation of edge atoms by hydrogen atoms also result in

Figure 1. Calculated phonon frequencies, Ω(k) of the bare armchair MoS2 nanoribbon with w=17.75 Å or n=12 (there are 36 atoms in the primitive cell) are presented along symmetry directions of the Brillouin zone using the small displacement method (SDM), and corresponding densities of states (DOS).
increasing the equilibrium lattice constant of these NRs are treated within supercell geometry using periodic boundary conditions. The stretching of the ribbon is achieved by segments of NRs and the edge atoms are saturated by H atoms as described in the text. Large (purple) and small (blue) balls are Mo, S, and H atoms. 

Figure 2. (a) Energy band structure of bare A-MoS2NR having \( n = 12 \) and the width \( w = 17.75 \) Å. The band gap is shaded and the zero of energy is set at the Fermi level. At the right-hand side, charge density isosurfaces of specific states at the conduction and valence band edges are shown. (b) Same as part a, but the edge atoms are saturated by H atoms as described in the text. Large (purple), medium (yellow), and small (blue) balls are Mo, S, and H atoms, respectively. Short and dark arrows indicate the direction of the axes of nanoribbons. Total number of atoms in the unit cells are indicated.

For both A- and Z-MoS2NR the response of A-MoS2R to the strain is different from graphene. The calculated force constants \( k_{A} = 116.39 \) N/m and 92.38 N/m for A-MoS2 having \( n = 12 \) and Z-MoS2NR having \( n = 5 \), respectively. Similarly, the calculated in-plane stiffness \( C = 108.47 \) and 103.71 N/m for Z-MoS2NR. However, stretched ribbons can return to its original geometry when the tension is released. In the harmonic range, the force constant is calculated to be \( k = 116.39 \) N/m and 92.38 N/m for A-MoS2 having \( n = 12 \) and Z-MoS2NR having \( n = 5 \), respectively. The difference between the values of armchair and zigzag nanoribbon occurs due to different bond and edge directions. As the width of the nanoribbon goes to infinity these two values are expected to converge to a single value. The calculated values are smaller than the values of \( C = 292 \) and 239 N/m calculated for graphene and BN honeycomb armchair nanoribbons. Nevertheless, both calculated \( k \) and \( C \) values indicate the strength of 1H-MoS2. It should be noted that the \( k \) is approximately proportional to \( n \), but \( C \) is independent of \( n \) for large \( n \). Small deviations arise from the edge effects.

To allow more variational freedom and reconstruction, segments of these NRs are treated within supercell geometry using periodic boundary conditions and spin-polarized calculations are carried out. Each supercell, both having total of 108 atoms, contains three unit cells for armchair and six unit cells for zigzag nanoribbons, respectively. The stretching of the ribbon is achieved by increasing the equilibrium lattice constant \( c_{0} \) by \( \Delta c \), to attain the axial strain \( \epsilon = \Delta c / c_{0} \). We optimized the atomic structure at each increment of the strain, \( \Delta \epsilon = 0.01 \) and calculated the total energy under strain \( E_{\tau}(\epsilon) \). Then the strain energy can be given by, \( E_{\tau} = E_{\tau}(\epsilon) - E_{\tau}(\epsilon = 0) \); namely, the total energy at a given strain \( \epsilon \) minus the total energy at zero strain. The tension force, \( F_{\tau} = -\partial E_{\tau}(\epsilon) / \partial \epsilon \) and the force constant \( k = \partial^{2} E_{\tau} / \partial \epsilon^{2} \) are obtained from the strain energy. Owing to ambiguities in defining the Young’s modulus of honeycomb structures, one can use in-plane stiffness \( C = (1 / A_{0}) (\partial^{2} E_{\tau} / \partial \epsilon^{2}) \) in terms of the equilibrium area of the supercell, \( A_{0} \). The in-plane stiffness can be deduced from \( k \) by defining an effective width for the ribbon.

Electronic and Magnetic Properties. Similar to the single layer 1H-MoS2, its armchair nanoribbons (A-MoS2NR) are also semiconductors. The bare A-MoS2NR is a nonmagnetic, direct band gap semiconductor. Upon hydrogen termination of the edges, the band gap increases. Also the direct band gap shows variation with \( n \), like the family behavior of graphene nanoribbons. However, unlike armchair graphene nanoribbons, the band gaps of A-MoS2NR’s do not vary significantly with its width \( w \) or \( n \). For narrow armchair nanoribbons with \( n < 7 \) the calculated value of the band gap is larger than that of wide nanoribbons due to quantum confinement effect. The variation of \( E_{\tau} \) with \( n \) is in agreement with that calculated by Li et al.\(^{48}\)
The electronic band structure and charge density of specific states are examined in detail for a bare A-MoS$_2$NR of $n = 12$ in Figure 2a. The edge states, which are driven from Mo-4d and S-3p orbitals and have their charge localized at the edges of the nanoribbon, form flat bands located in the large band gap of 1H-MoS$_2$. Because of these edge states, the band gaps of bare armchair nanoribbons are smaller than that of 1H-MoS$_2$. Upon termination of each Mo atom at the edge by two hydrogen and each S atom by a single hydrogen atom, the part of edge states are discarded and thus the band gap slightly increases. As seen in Figure 2b, the remaining edge states continue to determine the band gap of the ribbon. Even if the character of these bands changes, their charges continue to be located near the edge of the ribbon. Nevertheless, the band gaps of hydrogen saturated armchair nanoribbons remain to be smaller than that of 2D 1H-MoS$_2$.

Furthermore, we investigated the variation of band gap of hydrogen saturated armchair nanoribbons as a function of $n$. As shown in Figure 3 for $n \leq 7$ the values of band gap are larger due to quantum confinement effect, but for $n \geq 7$ they tend to oscillate showing a family like behavior. These oscillations follow those found for bare armchair nanoribon. All calculated A-MoS$_2$NR are found to be direct band gap semiconductors.

In contrast to A-MoS$_2$NR, the bare zigzag nanoribbons Z-MoS$_2$NR are spin-polarized metals. Here we consider Z-MoS$_2$NR with $n = 6$ as a prototype. In Figure 4, it is shown that the edge atoms of this nanoribbon undergo a (2 $\times$ 1) reconstruction by lowering its total energy by 0.75 eV. Interestingly, as a result of reconstruction, the bare Z-MoS$_2$NR is a half-metal with integer magnetic moment per primitive cell, namely $\mu = 2\mu_B$. Thus, the nanoribbon is metallic for majority (spin-up) bands, but a semiconductor for minority (spin-down) bands with an indirect band gap of $\sim 0.50$ eV. We check that half-metallic state of bare Z-MoS$_2$NR is maintained for $n = 5$, and $n = 8$. Half-metallic properties are interesting spintronic materials and were revealed first in 3D crystals. Lately, various nanostructures, such as Si nanowires and atomic chains of carbon-transition metals compounds have found to display half-metallic properties. The half-metallic property is destroyed upon the saturation of the edge atoms by hydrogen. The magnetic moment of the ribbon and the density of spin states at the Fermi level depend on how Mo and S atoms at the edges of the ribbon are passivated by hydrogen. One distinguishes three different hydrogen passivations, each leads to different magnetic moments as indicated in Figure 4. As the number of passivating hydrogen atoms increases the number of bands crossing the Fermi level decreases. However the spin-polarization is relatively higher, if each S atoms at one edge are passivated by single hydrogen atom and each Mo atom at the other edge is passivated by double hydrogen. Interestingly, the latter nanoribbon in Figure 4d is metallic for one spin direction and semimetal for the opposite spin direction. Different spin polarizations found for different spin directions can make potential nanostructure for applications in spintronics.

Earlier Li et al. examined electronic and magnetic properties of armchair and zigzag Mo$_x$S$_n$ nanoribbons using VASP within DFT. They found that armchair nanoribbons are non-magnetic semiconductors and their direct energy band gap vary with $n$ and becomes 0.56 eV as $n \to \infty$. They did not consider hydrogen passivation of edge atoms. They also noted that the value of net magnetic moment can change, but the ferromagnetic state of zigzag nanoribbons are maintained even after H passivation of edge atoms. Mendez et al. investigated armchair...
nанорibbons and concluded that these nanoribbons are metallic and have a net magnetic moment, but they change to semiconductor after hydrogen passivation of edge atoms. Their calculations show that in the case of bare armchair nanoribbons, the magnetic state is energetically more favorable by 14 meV and for H-saturated zigzag nanoribbons the antiferromagnetic state is favorable relative to the ferromagnetic state by 15 meV. These results disagree with the present results, as well as with those of Li et al.48

Normally, the bare and unreconstructed zigzag nanoribbons have sizable charged dipole moment along the direction from the edge having only negatively charged S atoms to the other edge having only positively charged Mo atoms. The dipole moment is calculated to be 55.4 eÅ per cell of Z-MoS₂NR having n = 6, but it reduces to 0.07 Å upon reconstruction of the edges. Present results show that the edge reconstruction ought to be treated properly to reveal the half-metallic state and to estimate the correct dipole moment.

**Figure 5.** Top and side views for the schematic representation of possible adsorption geometries of adatoms obtained after the structure optimization. Adatoms, Mo, and S are represented by red (large-dark), purple (medium-gray), and yellow (small-light) balls, respectively. Side view optimizes the heights of adatoms from Mo- or S-planes are calculated relative to the average heights of Mo- and S-atoms in the corresponding planes. The binding energy, $E_b$ is calculated as $E_b = E_{ad} + E_{A-MoS} - E_{ad-A-MoS}_r$. Here, $E_{ad}$ is the ground state energy of free adatom calculated in the same supercell with the same parameters; $E_{A-MoS}$ is the total energy of nanoribbon and $E_{ad-A-MoS}$ is the energy of adatom + A-MoS₂NR complex. The charge at the adatom $\rho_{ad}$ is calculated using Bader analysis.58 The excess charge of the adatom is obtained by subtracting the charge at the adatom, $\rho_b$ from the valence charge of the adatom $Z_{ad}$, namely $\rho^* = Z_{ad} - \rho_b$. Accordingly $\rho^* < 0$ implies excess electron at the adatom site. Here the adatom + A-MoS₂NR complex attains net magnetic moment after the adsorption of transition metal atom, Co. Adsorption of C and O do not cause any spin polarization in all adsorption geometries.

**Table 1.** Calculated Values of Adatoms Adsorbed to the Bare Armchair MoS₂ Nanoribbon Having n = 12 MoS₂ Units in the Primitive Unit Cell

<table>
<thead>
<tr>
<th>atom</th>
<th>site</th>
<th>$h_{Mo}$ (Å)</th>
<th>$h_{S}$ (Å)</th>
<th>$d_{Mo}$ (Å)</th>
<th>$d_{S}$ (Å)</th>
<th>$E_b$ (eV)</th>
<th>$\mu_v$ (µB)</th>
<th>$\rho^*$ (e)</th>
<th>$\Phi$ (eV)</th>
<th>$P$ (e × Å)</th>
<th>$E_A$, spin-up</th>
<th>$P^*$, spin-down states</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>NR₁</td>
<td>0.63</td>
<td>0.95</td>
<td>1.95</td>
<td>1.81</td>
<td>5.69</td>
<td>-0.07</td>
<td>5.60</td>
<td>-22.45, 0.63, -0.15</td>
<td>-15.05, -9.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR₂</td>
<td>0.01</td>
<td>1.55</td>
<td>2.00</td>
<td>1.79</td>
<td>6.35</td>
<td>-0.56</td>
<td>5.43</td>
<td>-26.58, 0.52, -0.02</td>
<td>-15.63, -8.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>NR₂</td>
<td>0.00</td>
<td>1.56</td>
<td>1.72</td>
<td>3.56</td>
<td>6.67</td>
<td>-0.73</td>
<td>5.64</td>
<td>0.84, 1.52, 0.00</td>
<td>-5.82, -5.81, -5.63, -1.16, -0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>NR₂</td>
<td>0.11</td>
<td>1.45</td>
<td>2.40</td>
<td>2.15</td>
<td>4.81</td>
<td>1.00</td>
<td>2.22</td>
<td>3.15, 0.04, -0.09</td>
<td>-1.12, -0.40, -0.36, -0.31, 0.38, 0.38, 1.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR₁</td>
<td>-0.02</td>
<td>1.55</td>
<td>2.32</td>
<td>2.17</td>
<td>4.44</td>
<td>0.85</td>
<td>0.26</td>
<td>5.19</td>
<td>-13.83, -1.45, -0.03</td>
<td>-0.95, 0.16, 0.29, 0.56, 1.17, 1.23</td>
<td></td>
</tr>
</tbody>
</table>

*The supercell in calculations consist of three primitive cells. There are two different adsorption sites as (described in Figure 5) for each adatom. The positions only with a positive binding energy are indicated. Key: $h_{Mo}$, the height of the adatom from Mo layer; $h_{S}$, the height of the adatom from the nearest S-layer; $d_{Mo}$, the adatom-nearest Mo distance; $d_{S}$, the adatom-nearest S distance; $E_b$, adatom binding energy; $\mu_v$, magnetic moment per supercell in Bohr magneton $\mu_B$; $\rho^*$, excess charge on the adatom (where negative sign indicates excess electrons); $\Phi$, photoelectric threshold (work function); $P$, dipole moment calculated in the x, y and z direction, respectively. Nanoribbon is in the (x,y)-plane and along the x-direction. $E_A$ energies of localized states induced by adatoms. Localized states are measured from the top of the valence bands in electron volt. The occupied ones are indicated by bold numerals and their spin alignments are denoted by either ↑ or ↓. States without indicated spin alignment are nonmagnetic.
moment in the y-direction, which is normal to the ribbon. Since adatom—adatom interaction is hindered due to large supercell dimensions, the localized states form flat bands in the supercell geometry. For C and O localized states deep in the valence band are generally due to their low energy 2s-states. For Co adatom most of the localized states originate from 3d-orbitals.

We note that, previously, He et al. found that the lowest energy adsorption position of C adatom is at the top of Mo atom in monolayer MoS2 and oxygen adatom is adsorbed to the top site above the S atom. However, adsorption of adatoms at the edges of the MoS2 nanoribbon gives rise to properties rather different from those in 1H-MoS2.

Vacancy Defects in MoS2 NR. We investigated five different types of vacancy defects, namely Mo-, S-vacancy, MoS-, S2-vacancy, and MoS2-triple vacancy, which are formed near the center of hydrogen passivated armchair (n = 12) and zigzag (n = 6) nanoribbons. All structures are optimized after the creation of each type of vacancy. Vacancy energies EV are calculated by subtracting the sum of the total energy of a structure having a particular vacancy type and the total energy(ies) of missing atoms in the vacancy defect from the total energy of the perfect structure (without vacancy). Here all structures are optimized in their ground states (whether magnetic or nonmagnetic). Positive EV indicates that the formation of vacancy defect is an endothermic process. In Table 2 calculated vacancy energies as defined above and their magnetic ground states are presented.

For a hydrogen saturated armchair nanoribbon (A-MoS2NR), having width n = 12, the vacancy defects are treated in a supercell geometry, where a single defect is repeated in every four unit cell. For this supercell configuration, vacancy—vacancy coupling becomes minute and the resulting defect states appear as flat bands. Similar to 1H-MoS2, all the vacancy types have zero net magnetic moments, except MoS2-triple vacancy, which has a net magnetic moment of μ = 2μB per supercell. The nonmagnetic excited states associated with vacancy defects occur above ∼120 meV, and are derived from Mo-4d and S-3p orbitals around the vacancy.

Similar to the armchair nanoribbons, various vacancy and divacancy defects in the hydrogenated zigzag nanoribbon (Z-MoS2NR), having width n = 6 are treated in a supercell geometry, where a single defect is repeated in every eight unit cell. Calculated vacancy energies, net magnetic moments per cell are presented in Table 2. It is found that in the presence of a vacancy defect, such as MoS-divacancy, S2-divacancy, Mo-vacancy and S-vacancy, the spin-polarization of the zigzag nanoribbons appears to be suppressed. For example, while defect free, zigzag nanoribbons are metallic and spin-polarized ground state with net magnetic moment of μ = 2.24μB per double unit cell, the total magnetic moment of eight unit cell decreases to 2−μ = 8.30μB per supercell from μ = 8.96μB in the presence of vacancy defects. In particular, the net magnetic moment of MoS2-triple vacancy appears to compensate for the edge magnetization of the zigzag MoS2 NR to result in a net magnetic moment of 8.67μB per supercell.

DISCUSSION AND CONCLUSIONS

The phonon dispersion of bare A-MoS2NR with n = 12 is calculated and stability of nanoribbons are ensured. Armchair nanoribbons are nonmagnetic direct band gap semiconductors; their energy band gaps vary with its width and termination of edge atoms with hydrogen, whereas zigzag nanoribbons are found to be ferromagnetic metals. The bare zigzag nanoribbon is found to be a half-metal. Both nanoribbons are stiff materials, but their in-plane stiffness are calculated to be less than half of those of graphene and BN.

The adsorption of adatoms and creation of vacancy defects in MoS2 nanoribbons have crucial effects in the electronic and magnetic properties. We found that several adatoms can be adsorbed readily at diverse sites with significant binding energy. In this respect, MoS2 appears to be a material, which is suitable for functionalization. Similarly, net magnetic moment can be achieved through the adsorption of Co adatoms to the non-magnetic armchair nanoribbons. In addition to spin-polarization, significant charges are transferred to (or from) adatom.

While vacancy defects of S, S2, Mo, and MoS created in hydrogen passivated armchair nanoribbon do not induce any magnetic moment, the creation of MoS2 triple vacancy results in a significant magnetic moment in the system. Vacancy creation in hydrogen passivated zigzag nanoribbons however suppresses the magnetic moment occurring at the edges of the nanoribbon and results in a decrease in the total magnetic moment of the system. Briefly, functionalization of MoS2 nanoribbons through adatom adsorption and vacancy creation appears to be a promising way to extend the application of MoS2.

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