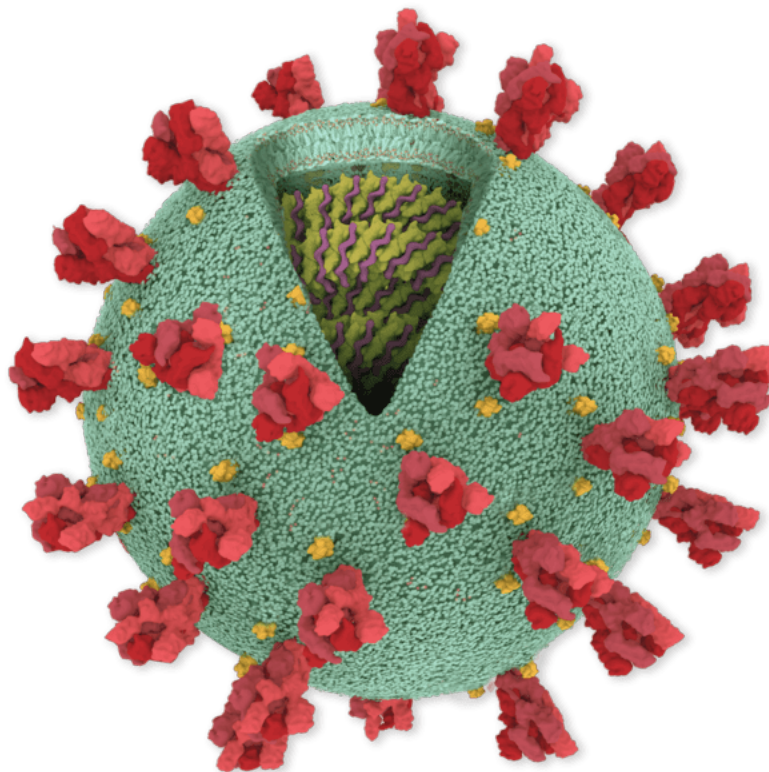


Bad News Wrapped in Protein: Inside the Coronavirus Genome

By Jonathan Corum and Carl Zimmer April 3, 2020



A virus is “simply a piece of bad news wrapped up in protein,” the biologists Jean and Peter Medawar wrote in 1977.

In January, scientists deciphered a piece of very bad news: the genome of SARS-CoV-2, the virus that causes Covid-19. The sample

came from a 41-year-old man who worked at the seafood market in Wuhan where the first cluster of cases appeared.

Researchers are now racing to make sense of this viral recipe, which could inspire drugs, vaccines and other tools to fight the ongoing pandemic.

A String of RNA

Viruses must hijack living cells to replicate and spread. When the coronavirus finds a suitable cell, it injects a strand of RNA that contains the entire coronavirus genome.

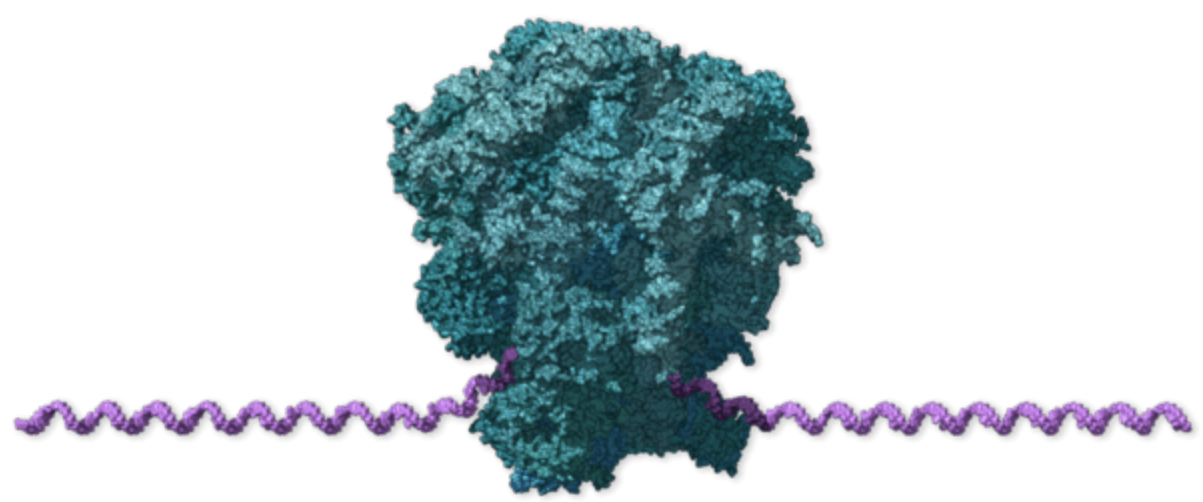


The genome of the new coronavirus is less than 30,000 “letters” long. (The human genome is over 3 billion.) Scientists have identified genes for as many as 29 proteins, which carry out a range of jobs from making copies of the coronavirus to suppressing the body’s immune responses.

The first sequence of RNA letters reads:

```
auuaaagguuuauaccuucccagguaacaaaccaaccaacuucgaucucuuguagaucuguucucuaa  
acgaacuuuaaaucuguguggcugucacucggcugcaugcuuagugcacucacgcaguaauuaaaua  
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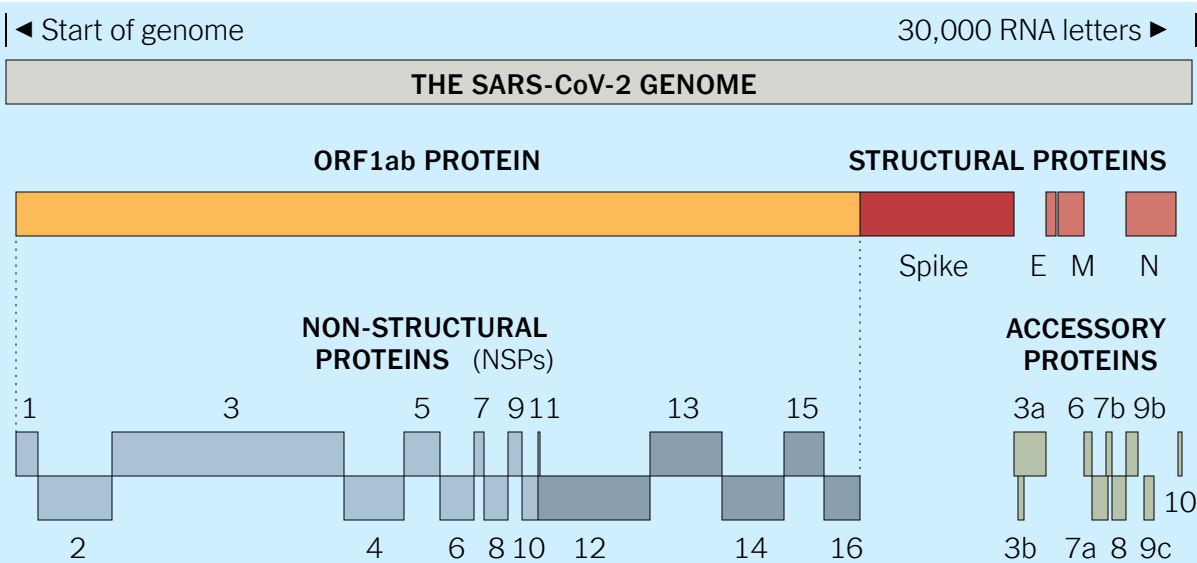
This sequence recruits machinery inside the infected cell to read the RNA letters — a, c, g and u — and translate them into coronavirus proteins.



The full coronavirus genome and the proteins it encodes are shown below.

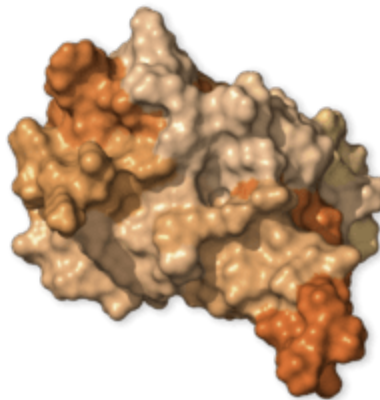
A Chain of Proteins · ORF1ab

The first viral protein created inside the infected cell is actually a chain of 16 proteins joined together. Two of these proteins act like scissors, snipping the links between the different proteins and freeing them to do their jobs.



Research on other coronaviruses has given scientists a good understanding of what some of the SARS-CoV-2 proteins do. But other proteins are far more mysterious, and some might do nothing at all.

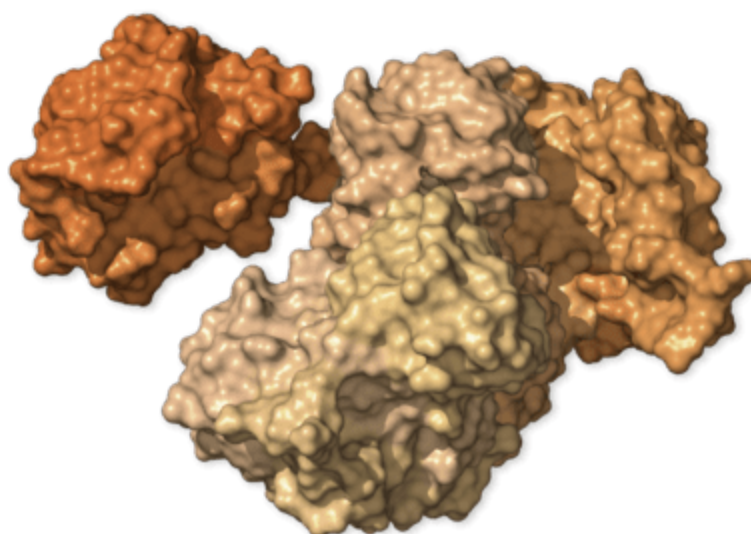
Cellular Saboteur · NSP1



This protein slows down the infected cell's production of its own proteins. This sabotage forces the cell to make more virus proteins and prevents it from assembling antiviral proteins that could stop the virus.

```
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Mystery Protein · NSP2

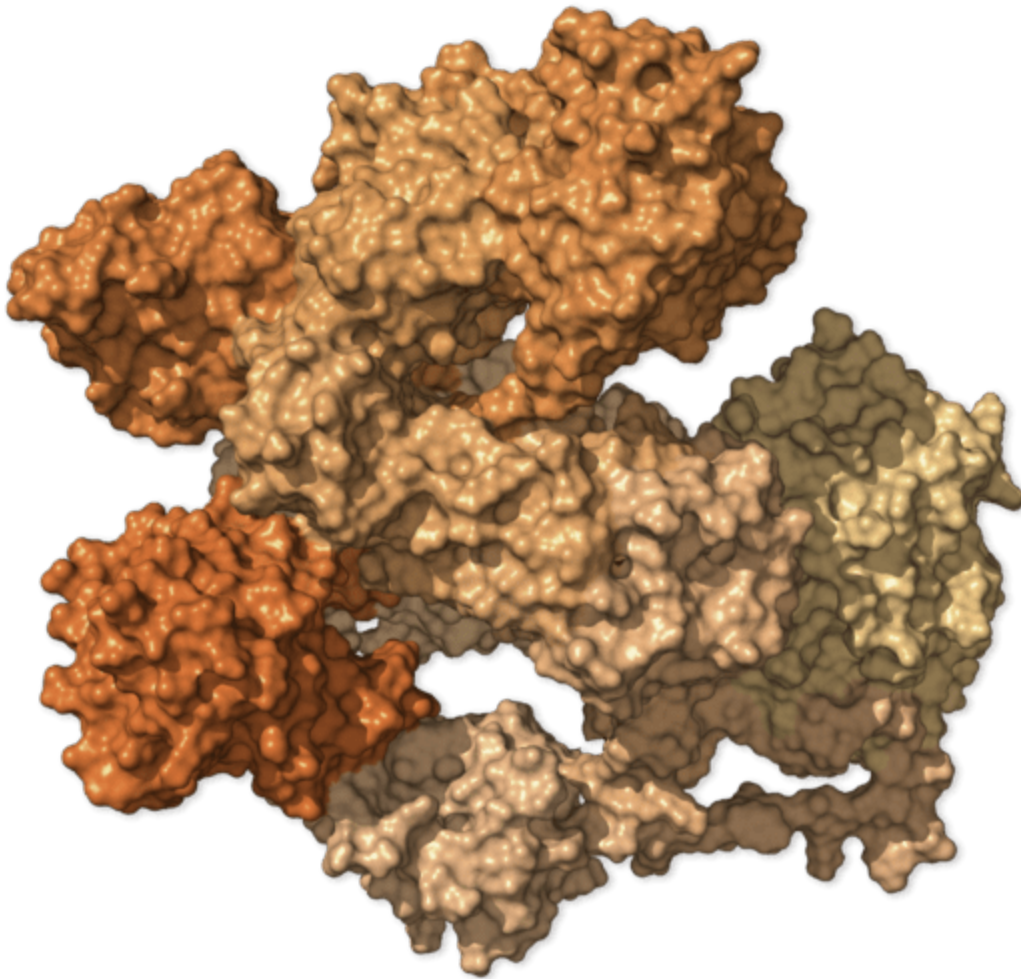


Scientists aren't sure what NSP2 does. The other proteins it attaches to may offer some clues. Two of them help move molecule-filled bubbles called endosomes around the cell.

```
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Untagging and Cutting · NSP3



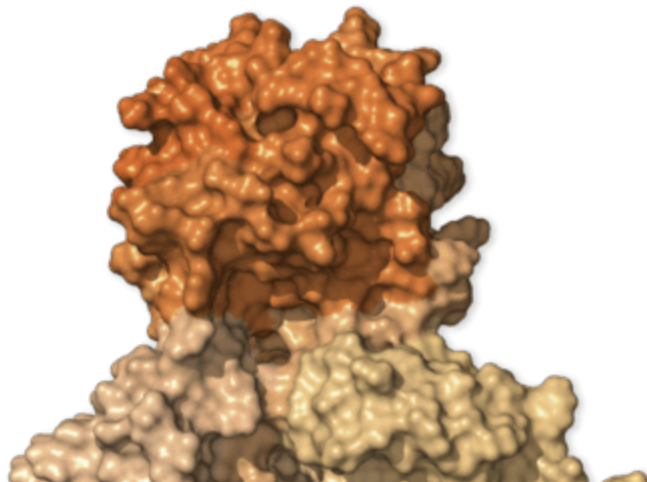
NSP3 is a large protein that has two important jobs. One is cutting loose other viral proteins so they can do their own tasks. It also alters many of the infected cell's proteins.

Normally, a healthy cell tags old proteins for destruction. But the

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Bubble Maker · NSP4





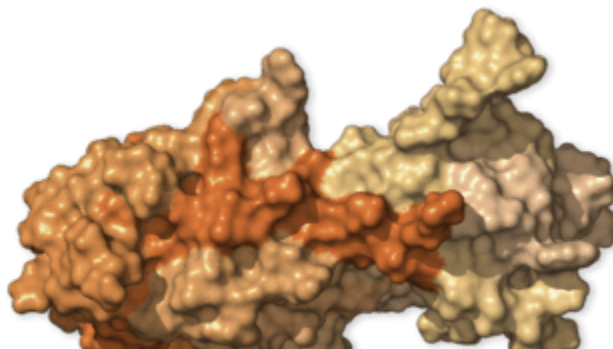
Combining with other proteins, NSP4 helps build fluid-filled bubbles within infected cells. Inside these bubbles, parts for new copies of the virus are constructed.

```

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Protein Scissors · NSP5

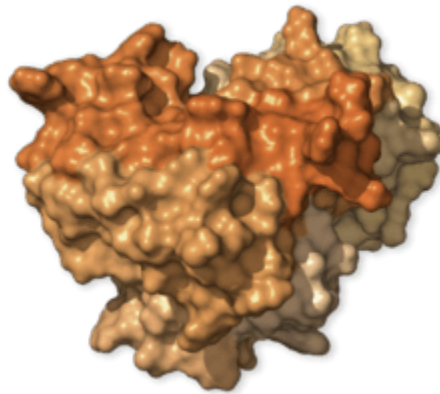




This protein makes most of the cuts that free other NSP proteins to carry out their own jobs.

```
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Bubble Factory · NSP6

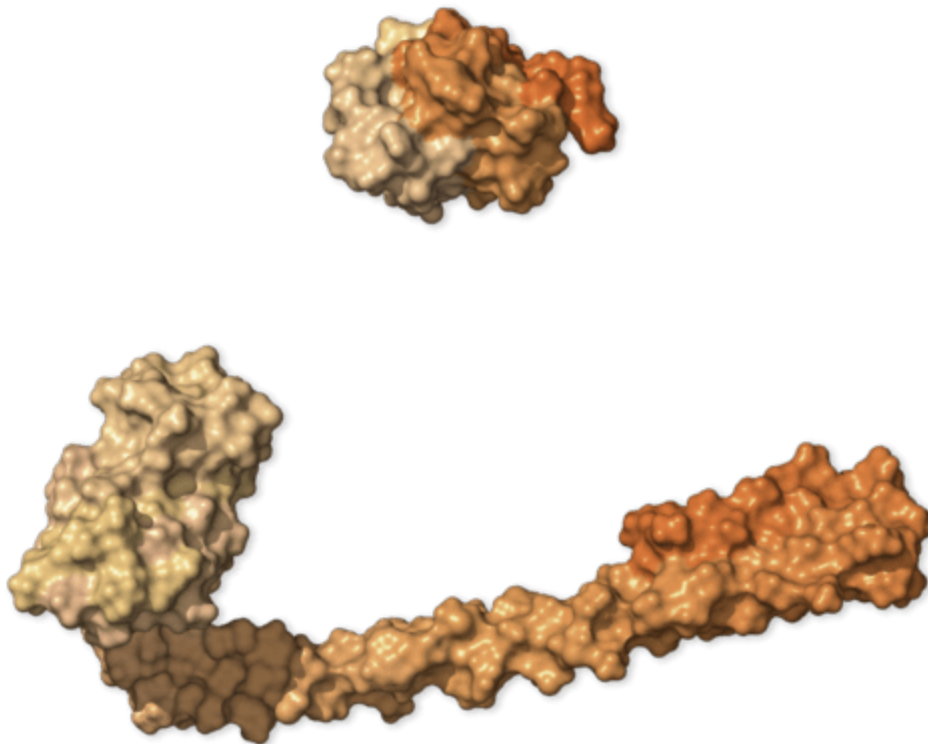


Works with NSP3 and NSP4 to make virus factory bubbles.

```
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Copy Assistants · NSP7 and NSP8



These two proteins help NSP12 make new copies of the RNA genome, which can ultimately end up inside new viruses.

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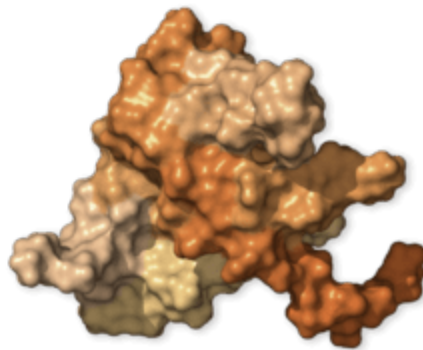
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```

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```

At the Heart of the Cell · NSP9



This protein infiltrates tiny channels in the infected cell's nucleus, which holds our own genome. It may be able to influence the movement of molecules in and out of the nucleus — but for what purpose, no one knows.

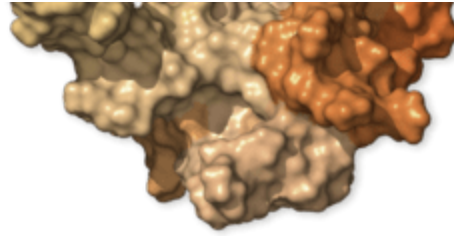
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```

Genetic Camouflage · NSP10

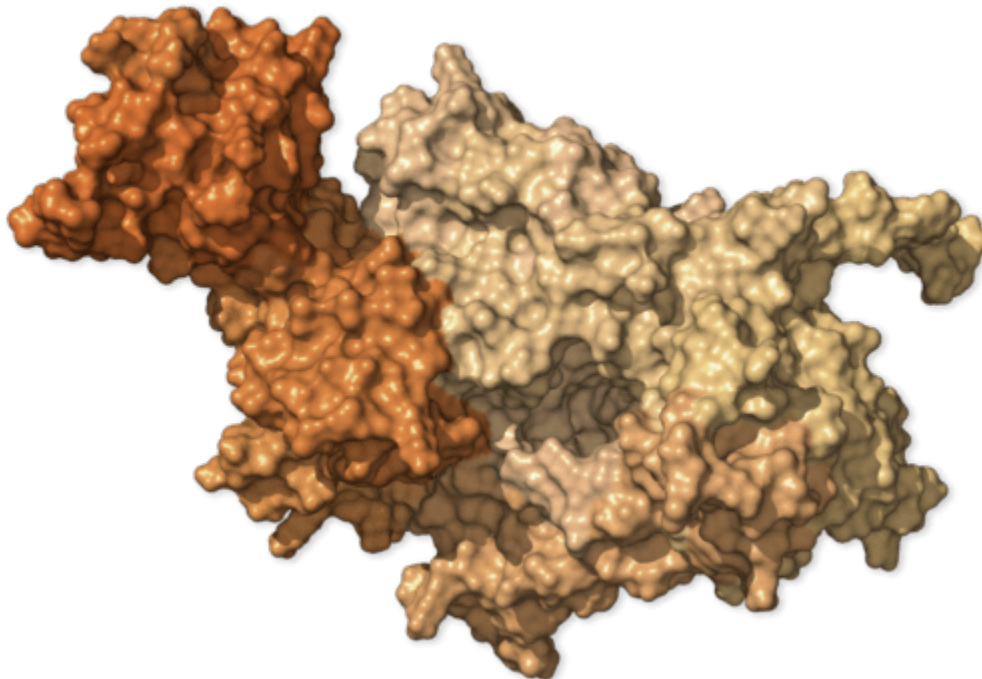




Human cells have antiviral proteins that find viral RNA and shred it. This protein works with NSP16 to camouflage the virus's genes so that they don't get attacked.

```
gcugguaaugcaacagaagugccugccaauucaacuguaauaucuuucugugcuuuugcuguagaugcu  
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gucuguaccgucugcgguauguggaaaggguuauuggcuguaguugugaucaacuccgcgaaccaugcuu  
cag
```

Copy Machine · NSP12



This protein assembles genetic letters into new virus genomes. Researchers have found that the antiviral remdesivir interferes with NSP12 in other coronaviruses, and trials are now underway to see if the drug can treat Covid-19.

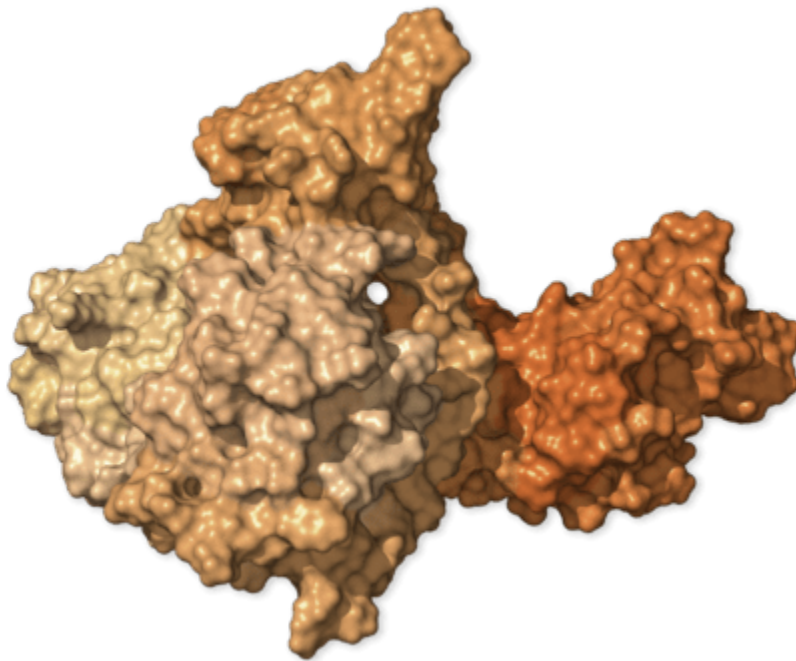
As the infected cell reads the RNA sequence for NSP12 :

ucagcugaugcacaaucguuuuuaaca. . .

It slips a little, then continues reading:

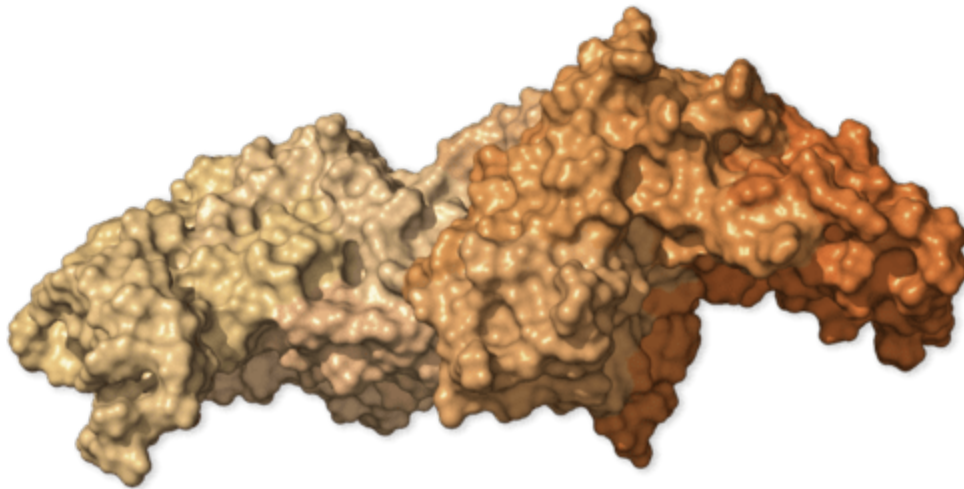
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Unwinding RNA · NSP13



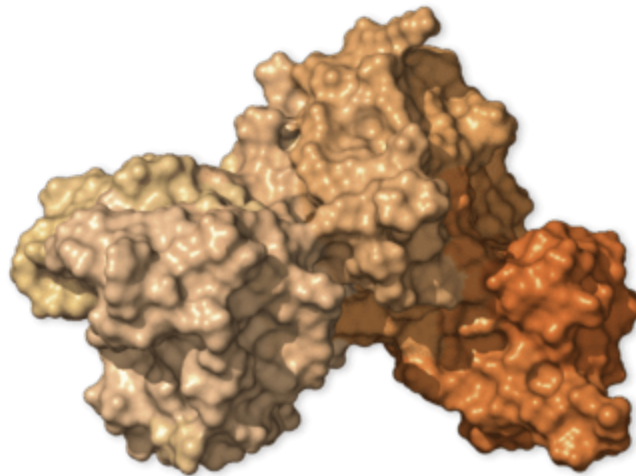
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Viral Proofreader · NSP14

[illegible]

aaccaccgcgcuggagaucaauuuuaaacaccucuaaccacuuauuguaacaaaggacuucccuuggaaugua
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Cleaning Up · NSP15

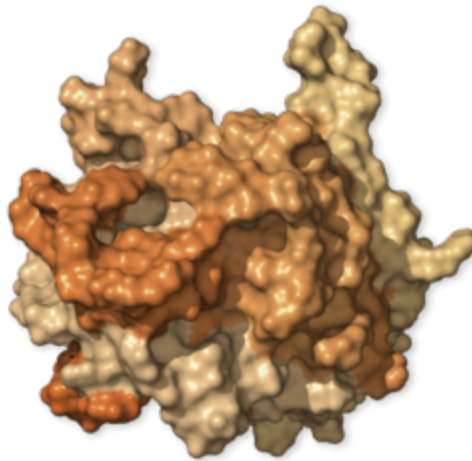


Researchers suspect that this protein chops up leftover virus RNA as a way to hide from the infected cell's antiviral defenses.

agaguuuagaaaauguggcuuuuaauguuguaaaauaagggacacuuugauggacaacaggggugaaguac
caguuuucuaucuuuaaauaacacuguuuacacaaaaguugaugguguugauguagaauuguuugaaaaua
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uacaa

More Camouflage · NSP16

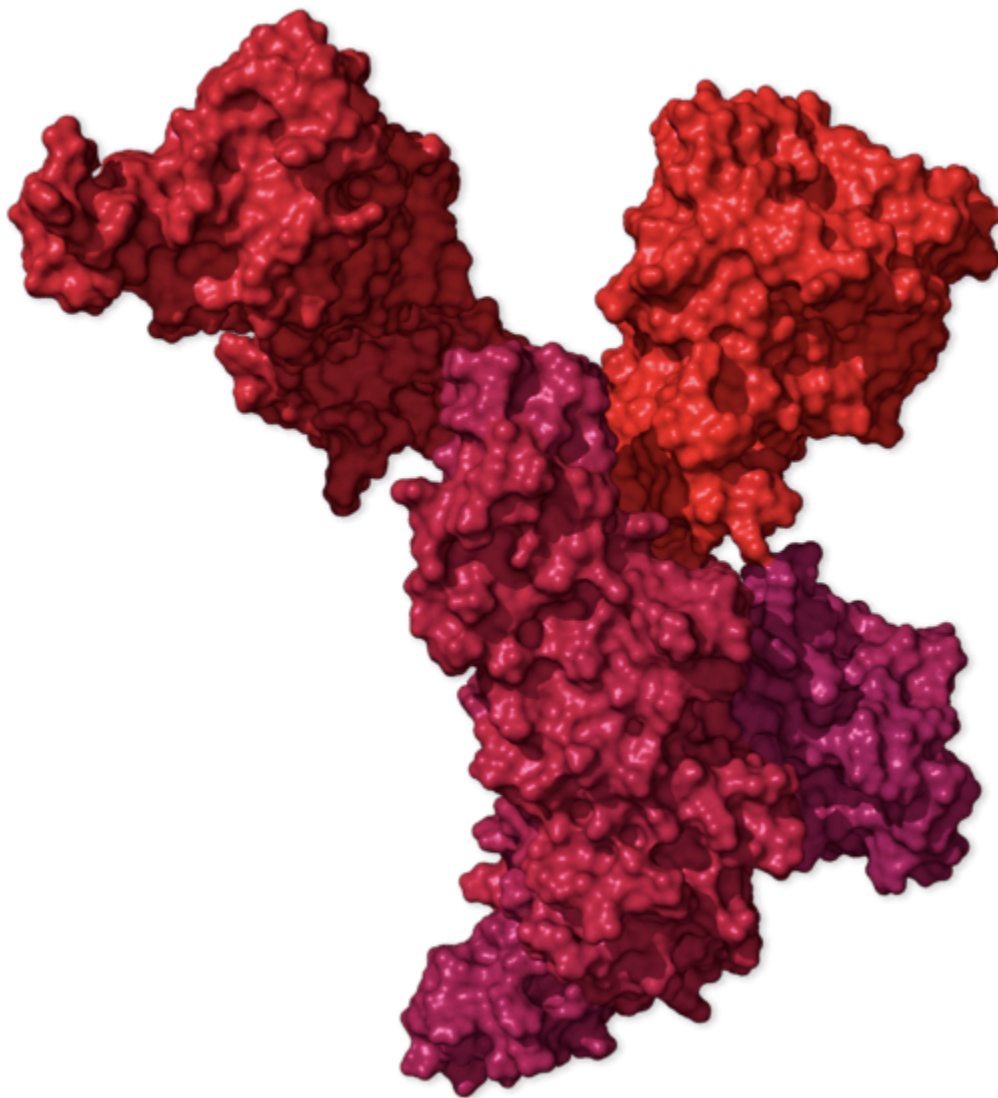


NSP16 works with NSP10 to help the virus's genes hide from proteins that chop up viral RNA.

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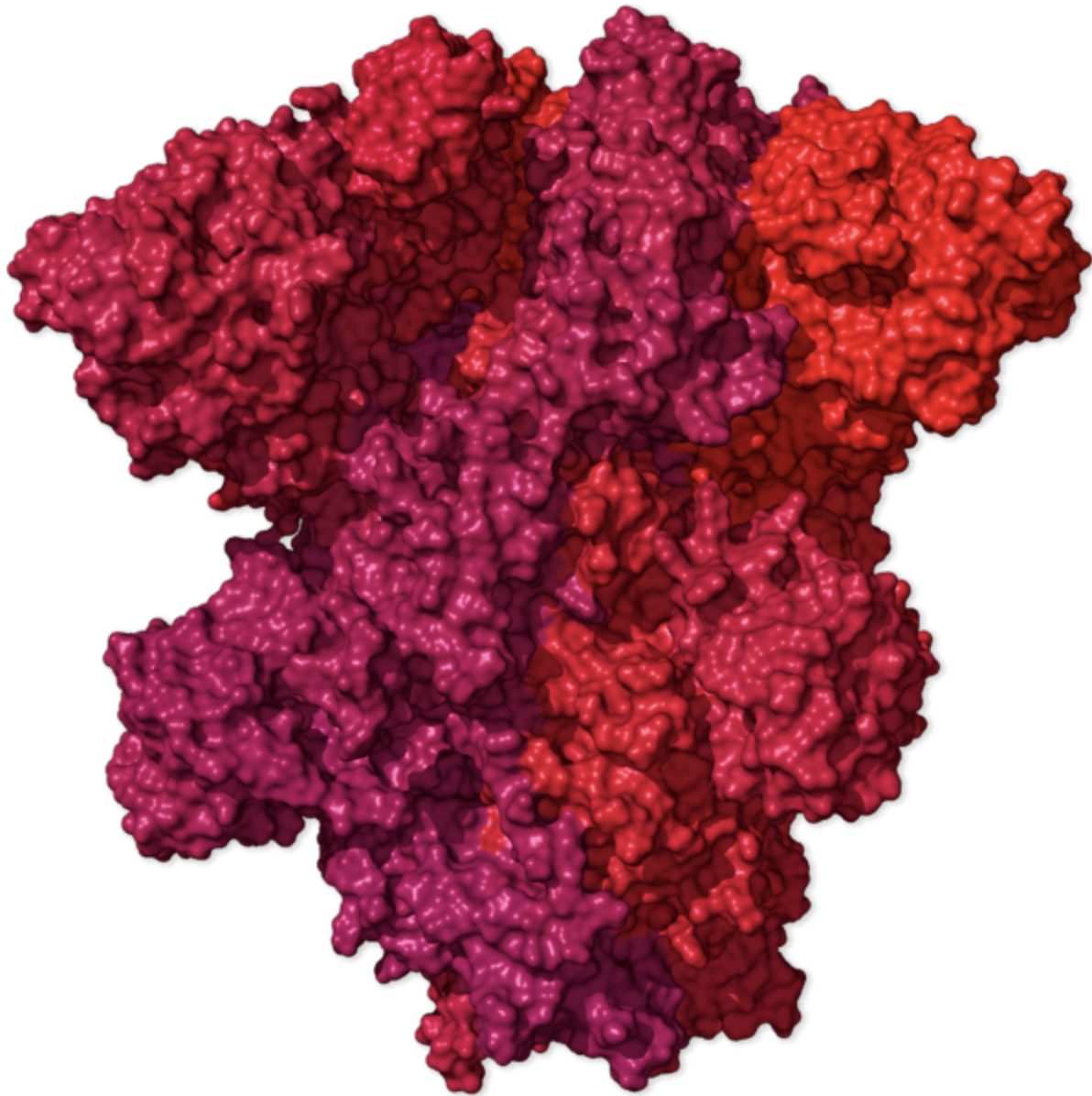
Spike Protein · S

The spike protein is one of four structural proteins — S, E, M and N — that form the outer layer of the coronavirus and protect the RNA inside. Structural proteins also help assemble and release new copies of the virus.



The S proteins form prominent spikes on the surface of the virus

by arranging themselves in groups of three. These crownlike spikes give coronaviruses their name.



Part of the spike can extend and attach to a protein called ACE2 (in yellow below), which appears on particular cells in the human airway. The virus can then invade the cell.



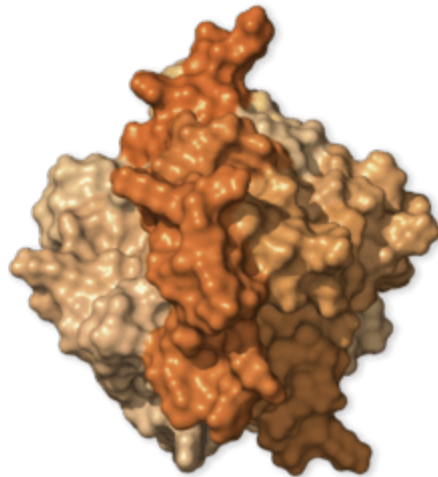


The gene for the spike protein in SARS-CoV-2 has an insertion of 12 genetic letters: `ccucggcgggca`. This mutation may help the spikes bind tightly to human cells — a crucial step in its evolution from a virus that infected bats and other species.

[illegible]


```
uuuauagcuggcuugauugccauaguaaugggugacaauuauugcuuugcuguaugaccaguugcuguagu
ugucucaagggcuguuguucuuguggauccugcugcaauuugaugaagacgacucugagccagugcuc
aaaggagucaauuacauuacacauaaacgaacuu
```

Escape Artist · ORF3a



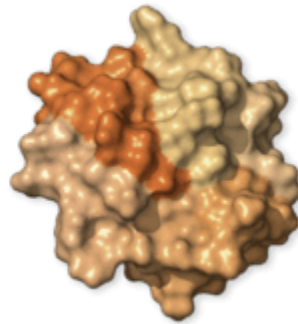
The SARS-CoV-2 genome also encodes a group of so-called “accessory proteins.” They help change the environment inside the infected cell to make it easier for the virus to replicate.

The ORF3a protein pokes a hole in the membrane of an infected cell, making it easier for new viruses to escape. It also triggers inflammation, one of the most dangerous symptoms of Covid-19.

```
auggauuuguuuauagagaauucacaauggaacuguaacuugaagcaaggugaaaaucaaggauugu
acuccuucagauuuuguucgcuacugcaacgauaccgauacaagccucacuccuuucggauggcuu
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ggaguuguuaauccaguaauuggaaccauuuugaugaaccgacgacgacuacugcugccuuuguuaa
gcacaagcugaugaguacgaacuu
```

ORF3b overlaps the same RNA, but scientists aren't sure if SARS-CoV-2 uses this gene to make proteins.

Envelope Protein · E



The envelope protein is a structural protein that helps form the oily bubble of the virus. It may also have jobs to do once the virus is inside the cell. Researchers have found that it latches onto proteins that help turn our own genes on and off. It's possible that pattern changes when the E protein interferes.

auguacucauucguuucggaagagacagguacguaaauaguuauagcguacuuccuuuuucugcuuuc
gugguauuccuugcaguuacacuaagccauccuacugcgcuuugauugugugcguacugcugcaauauu
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guuccugaucuuucuggucuaaacgaacuaaaauuuauuuaguuuucuguuuggaacuuuaauuuuag
cc

Membrane Protein · M

Another structural protein that forms part of the outer coat of the virus.

```
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auagguuuccuauuccuuacauaggauuugucuucuaacaauuugccuauugccaacaggaauagguuuuug
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acagaccuuccaguagcagugacaauauugcuuugcuuguacaguaagugacaacag
```

Signal Blocker · ORF6

This accessory protein blocks signals that the infected cell would send out to the immune system. It also blocks some of the cell's own virus-fighting proteins, the same ones targeted by other viruses such as polio and influenza.

```
auguuucaucucguugacuucagguuacuauagcagagauuuacuauuuuuuauaggagcuuuuuaa
```

guuuccauuuggaauucuugauuacaucauaaaccucauaauuaaaaauuuaucaagucacuaacugag
aauaaaaauucucaauuagaugaagagcaaccaauggagauugauuaaacgaac

Virus Liberator · ORF7a

When new viruses try to escape a cell, the cell can snare them with proteins called tetherin. Some research suggests that ORF7a cuts down an infected cell's supply of tetherin, allowing more of the viruses to escape. Researchers have also found that the protein can trigger infected cells to commit suicide — which contributes to the damage Covid-19 causes to the lungs.

augaaaauuauucuuuuucuuuggcacugauaacacucgcuacuugugagcuuuaucaacuaccaagagugu
guuagagguacaacaguacuuuuuaaagaaccuugcucuucuggaacauacgagggcaauucaccauuu
cauccucugcugauaacaauuugcacugacuugcuuuagcacucaauuugcuuuugcuuguccugac
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uauuccuuguuuuauuauugcuuauuauucuuuugguucucacuugaacugcaagaucuuuauuagaacuu
gucacgccuaaacgaac

ORF7b overlaps this same stretch of RNA, but it's not clear what, if anything, the gene does.

Mystery Protein · ORF8

The gene for this accessory protein is dramatically different in SARS-CoV-2 than in other coronaviruses. Researchers are debating what it does.

```
augaaauuucuuguuuuucuaggaaucaucacaaacuguagcugcauuucaccaagauguaguuuacag  
ucauguacucaacaucacaaccauauguaguugaugacccguguccuauucacuucuaauucuaaaugguau  
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ccuaaaauuggguagucuuguagugcguuguucguucuaugaagacuuuuuagaguaucaugacguucgu  
guuguuuuagauuucaucuaaacgaacaaacuaaa
```

Nucleocapsid Protein · N

The N protein protects the virus RNA, keeping it stable inside the virus. Many N proteins link together in a long spiral, wrapping and coiling the RNA:

```
augucugauaauggacccccaaaaucagcgaaaugcaccgcauuacguuugguggacccucagauuca  
acuggcaguaaccagaauggagaacgcagugggcgcgaucaaaacaacgucggcccaagguuuacc  
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cguuccucaucacguagucgcaacaguucaagaaauucaacuccaggcagcaguaggggaacuucuccu  
gcuagaauuggcuggcaauuggcgugaugcugcucuugcuuugcugcugcuugacagauugaaccagcuu  
gagagcaaaaugucugguaaaaggccaacaacaacaaggccaaacugucacuaagaaaucugcugcugag  
gcuucuaagaagccucggcaaaaacguacugccacuaaagcauacaauguaacacaagcuucggcaga
```

```
cgugguccagaacaaacccaaggaaaauuuggggaccaggaacuaaucagacaaggaacugauuacaaa  
cauuggccgcgaaaauugcacaauuugcccccagcgcuucagcguucuuucggaugucgcgcgauuggcaug  
gaagucacaccuucgggaacgugguugaccuacacaggugccaucaaaauuggaugacaaagaucacaaau  
uucaaagaucaagucuuuugcugaauaagcauuugacgcauacaaaacauucccaccaacagagccu  
aaaaaggacaaaaagaagaaggcugaugaaacucaagccuuaccgcagagacagaagaaacagcaaacu  
gugacucuucuccugcugcagauuuggaugauuucuccaaacaauugcaacaauccaugagcagugcu  
gacucaacucaggccuaaacucaugcagaccacacaaggcag
```

The accessory proteins ORF9b and ORF9c overlap this same stretch of RNA. ORF9b blocks interferon, a key molecule in the defense against viruses, but it's not clear if ORF9c is used at all.

Mystery Protein · ORF10

Close relatives of the SARS-CoV-2 virus don't have the gene for this tiny accessory protein, so it's hard to know what it's for yet — or even if the virus makes proteins from it.

```
augggcuaauaaaacguuuucgcuuuuccguuuacgauauauagucuaucucuugugcagaauaauucu  
cguacuacauagcacaaguagauguaguuuacuuuaucucacauag
```

End of the Line

The coronavirus genome ends with a snippet of RNA that stops the cell's protein-making machinery. It then trails away as a repeating sequence of aaaaaaaaaaaaaa

```
caaucuuuaucaguguguaacauuagggaggacuugaaagagccaccacauuuucaccgaggccacgc  
ggaguacgaucgaguguaacagugaacaugcuagggagagcugccuauauggaagagcccuaaugugua  
aaauuaauuuuaguagugcuaucccaugugauuuuaauagcuucuuaggagaugacaaaaaaaaaa  
aaaaaaaaaaaaaaaaaaaaa
```

Note: The four letters of DNA are A, C, G and T. In RNA molecules like the coronavirus genome, the T (thymine) is replaced with U (uracil).

Sources: Fan Wu et al., Nature; National Center for Biotechnology Information; Dr. David Gordon, University of California, San Francisco; Dr. Matthew B. Frieman and Dr. Stuart Weston, University of Maryland School of Medicine; Dr. Pleuni Pennings, San Francisco State University; Journal of Virology; Annual Review of Virology.

Model sources: Coronavirus by Maria Voigt, RCSB Protein Data Bank headquartered at Rutgers University–New Brunswick; Ribosome from Heena Khatter et al., Nature; Proteins from Yang Zhang's Research Group, University of Michigan.